RESILIENCE OF WATER SUPPLY SYSTEMS IN MEETING THE CHALLENGES POSED BY CLIMATE CHANGE AND POPULATION GROWTH

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Resilience, Potable water supply, Meta-system, Climate change, Population growth, System Dynamics modeling, Indicators

Abstract

This research study focused on an investigation of resilience of water supply systems to climate change and population growth impacts. A water supply system is a complex system which encompasses a diverse set of subsystems which lie on socio-ecological and technical domains. The interrelationships among these subsystems dictate the characteristics of the overall water supply system. Climate change and population growth are two issues that create qualitative and quantitative impacts on surface water resources that influence the functions of a water supply system.

Due to the complexity of a water supply system and the dependability of water on climate conditions, provision of a reliable potable water supply is a challenge. Therefore, effective management of water supply is a key pre-requisite.

For achieving management goals in complex systems, complex procedures may be required. Depending on uncertain climatic conditions, one approach to satisfy demand on a water supply system is to expand the system by building new infrastructure. That is a part of a supply side improvement and management process. A completely different approach is to understand the system components, especially their characteristics and capabilities, in order to manage the relationships between them and make use of that knowledge to manipulate management strategies to achieve maximum efficiencies, thus obviating the need to resort to the commonly adopted option of new infrastructure provision.

Management strategies based on the knowledge of resilience are related to the second approach mentioned above. Such strategies allow for decision makers' timely reactions at trigger points to enable the formulation of the most appropriate management practices and also inform the correct time frame for new infrastructure development by acknowledging critical boundaries beyond which the system will not be able to function properly. The significance of this project is the exploration of the latter management approach discussed above through application of the resilience concept, in order to create new knowledge in the field of water supply.

In the absence of a formal method to evaluate resilience of a water supply system, an approach was developed to link resilience characteristics of the system to a surrogate measure. South East Queensland (SEQ) Water Grid was selected as a case study to

test the resilience of the system to climate change and population growth impacts. A system dynamics model of the SEQ Water Grid was developed and simulated under different water availability scenarios in order to evaluate the resilience characteristics of the system. The defined failure threshold was based on the demand. A set of indicators such as non-failure rainfall reduction percentage, design pressure to threshold pressure ratio (R_{pp}), service reduction ratio (R_{ss}), service reduction rate (R_{sp}), non failure ratio (R_{nf}) and recovery ratio (R_{rr}) were proposed to evaluate the system behaviour and logistic regression analysis was used as the evaluation method for future rainfall, storage and demand conditions.

For the SEQ Water Grid, the non-failure rainfall reduction percentage of 40% indicates that the system is capable of withstanding pressure (low rainfall) even for 40% reduced rainfall conditions (below average) for 50% storage. For 100% storage, the pressure withstanding capability increased up to 60% rainfall reduced conditions. In other words, the system has the ability to withstand 0.4 times above the 'design pressure' for 50% storage and 0.6 times above the 'design pressure' for 100% storage. The design pressure refers here to the level of disturbance (pressure) that the system was expected (designed) to cope without failure. The pressure in this case was the low rainfall conditions.

As per the proposed indicators, the service reduction ratio (R_{ss}) indicates the available service potential at the threshold pressure. For the SEQ Water Grid, (for 50% storage) R_{ss} value of 0.31 indicates that at threshold pressure, the supply potential is 31%. It can also be noted that the system is capable of providing service without failure until 31% drop of output at 50% storage. For 100% storage, the system is capable of providing services without failure until 28% drop in output. This indicates that the SEQ Water Grid has the ability to operate over a considerable range of pressure without failure, which indicates high resilience characteristics. The high (above 1) service reduction rate of 1.73 and 1.2 indicates that the system behaviour as a response to pressure variation is high.

For storage of 50% or above, the system's ability to recover is very high. The system recovers within two months after a twelve month low rainfall period. This fact is justified by the high non failure ratio of 0.97 indicating that for a twelve month low rainfall period for 97% of the duration, the system is capable of supplying a satisfactory level of service. The recovery ratio (R_{rr}) of 1 indicates that after recovery, the system is capable of providing its maximum level of service.

Therefore, the SEQ Water Grid is expected to perform as a high resilience system under the impacts of climate chance and increasing demand. It was also identified that loss of systemic resilience takes place at a faster rate as the rainfall, demand and storage become unfavourable. The trigger point for introducing the first level of water restrictions for the SEQ Water Grid should be when the storage levels reach approximately 40% of the capacity level.

The practical value of the study is that it includes the development of methodology for assessing the resilience of a water supply system which helps to understand the dynamic nature of a system and the adaptability to a changed environment, so that the operators of the system are knowledgeable about the maximum pressure levels, below which the system operates successfully. The evaluation of assessment results obtained by the knowledge created in this study allows the prevention of catastrophic failure of the system by identifying trigger points for early actions. The practical approach to enforcing water restrictions is related to the storage levels. Therefore, by relating the trigger points to the storage levels of reservoirs, the operator will be able to formulate the most appropriate water restriction levels if necessary.

List of Publications

Conference papers

- Amarasinghe, P., Barnes, Paul H., Egodawatta, P., McGree, J., Goonetilleke, A. (2013). An approach for identifying the limit states of resilience of a water supply system. Paper presented at the 9th Annual International Conference of the International Institute for Infrastructure Renewal and Reconstruction: Risk-informed Disaster Management: Planning for Response, Recovery & Resilience, Queensland University of Technology, Brisbane, QLD.

- Amarasinghe, P., Barnes, Paul., Egodawatta, P., Goonetilleke, A. (2012). Application of Resilience concept for enhanced management of water supply systems. Paper presented at the 2nd International Conference on Sustainable Built Environment, Kandy, Sri Lanka.

- Barnes, Paul H., Amarasinghe, P., Egodawatta, P., Goonetilleke, A. (2011). Assessing the resilience of potable water supplies in Southeast Queensland Australia. Paper presented at the International Conference on Building Resilience: Interdisciplinary approaches to disaster risk reduction and the development of sustainable communities, International Institute for Infrastructure Renewal and Reconstruction, Kandalama, Sri Lanka.

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Abbreviations

ABS	- Australian Bureau of Statistics
ADWG	- Australian Drinking Water Guidelines
BOD	- Biological Oxygen Demand
BOM	-Bureau of Meteorology
CIDA	- Canadian International Development Agency
CLD	- Causal Loop Diagram
COD	-Chemical Oxygen Demand
CSIRO	- Commonwealth Scientific Industrial and Research Organisation
DBP	- Disinfection By-Products
DERM	- Department of Environment and Resource Management
DO	- Dissolved Oxygen
DOM	- Dissolved Organic Matter
GHG	- Greenhouse Gases
HFC	- Hydro Fluoro Carbons
IPCC	- Intergovernmental Panel on Climate Change
LOS	-Level of Services
NHS	- NHS Institute for Innovation and Improvement, UK
PAH	- Polycyclic Aromatic Hydrocarbon
QWC	- Queensland Water Commission
SD	- Sytem Dynamics
SEQ	- South East Queensland
SFD	- Stock and Flow Diagram
TDS	- Total Dissolved Solids
TN	- Total Nitrogen
TP	- Total Phosphorus

UNAIDS	- United Nations programme on HIV/AIDS
WHO	- World Health Organization
WMO	- World Meteorological Organization
WSS	- Water Supply System

Statement of Original Authorship

The work contained in this thesis has not been previously submitted for a degree or diploma from any other higher education institute to the best of my knowledge and belief. The thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Pradeep Amarasinghe

Date: 08 / 10 /2014

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Dedication

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Chapter 1: Introduction

1.1 BACKGROUND

Reliability of water supply depends on the system's ability to provide a sufficient quantity of water of a specified quality to end users without disruptions. A water supply system is a combination of complex subsystems. Hence, the practice of water supply needs to consider many different processes. However, disturbing forces can act on a water supply system, reducing the supply potential. Two such recognised pressures are population growth and climate change.

Under normal operating conditions, a system operates within its capacity limits. When a pressure is acting on the system, firstly, it starts reducing the potential output levels (e.g. quantity and quality); and as the pressure keeps increasing, the system can completely stop functioning. The resulting impact of these pressures is reduction of the final output volume of potable water to consumers.

However, when designing a water supply system, it is not possible to incorporate safety factors to cope with all possible adverse pressures, especially the impacts of climate change due to the uncertainty involved in the prediction of climate change impacts. Therefore, the formulation of effective management strategies to reduce the potential adverse effects of pressures is gaining attention.

The concept of resilieince informs the ability of a system to undergo change, while still retaining functionality. Furthermore, resilience, as a concept, highlights characteristics such as the ability of the system to absorb pressures or disturbances, and re-organise. Resilience has not yet been widely applied to infrastructure management and offers significant operational value to improve reliability of supply under changing and uncertain pressures. Consequently, a thorough understanding of the concept of resilience, combined with the detailed evaluation of the interrelationships within water supply system processes, provides a way forward for improved management.

This thesis focuses on developing an approach for in-depth evaluation of the resilience characteristics of a water supply system to identify the most appropriate management practices for the provision of a reliable water supply from rain-fed catchments. The thesis then explores the application of this approach to provide improved guidance to system operators to enhance the efficiency and reliability of water supply.

1.2 DESCRIPTION OF THE PROJECT

To investigate the application of resilience to water supply management, this thesis focusses on the analysis of the operational processes of a water supply system; the formulation of an approach to assess the resilience of the system with respect to climate change and population growth-related pressures; and application of the knowledge created to a selected system (as a case study). Accordingly, defining the 'system' including subsystems, and evaluating the inter-dependability of the key processes are critical.

A complete rain-fed water supply system consists of three main processes: water storage; water treatment; and water distribution. These processes takes place in different domains which represent different subsystems: the water supply catchment; the water treatment plant; and the water distribution network.

The first process, water storage, takes place within the water supply catchment subsystem. Storage is determined by two key factors: *Storage capacity;* and *inflow* (primarily from surface runoff and streamflow). Therefore, any impact on the inflow to the reservoir will directly influence the quantity of water available in storage.

All the other processes depend on the availability of water in the storage. Consequently, available water is the most essential element in the water supply system. Therefore, water inflow, that influences water storage, is one of the primary determinants of the successful functioning of the entire water supply system. The water supply catchment is a part of an ecological system, as such water inflow depends on many complex interactions of ecological, hydrological and meteorological activities.

The second process, the water treatment system and the water treatment plant, is essential as raw water is not always of potable quality due to changes in ecological, hydrological and meteorological activities. Water treatment plants are constructed to treat raw water to potable quality. Minor water quality deterioration will not affect overall service delivery as the treatment plant is generally capable of treating raw water to the required standard. However, in the case of major deterioration of raw water quality, the treatment plant may not be able to cope, and the rate of treatment will decrease dramatically, lowering the performance of the system. A water treatment plant and associated infrastructure can be considered as a technical system.

The third process, distribution to the end users, is the final component of a water supply system. Distribution depends on demand, and demand depends on the user population and their usage characteristics. Therefore, when designing a water supply system, the current demand, usage characteristics, as well as future population growth potential needs to be considered. Storage and treatment capacities are designed with due consideration to these factors. The end users are also part of a broader social system.

Therefore, a water supply system is a combination of ecological, technical and social subsystems. Interconnection of these three subsystems forms a ‘meta-system’. Successful service delivery at the end can be expected only if the processes within each subsystem progress well and interact successfully. Figure 1.1 illustrates a water supply system as a ‘meta-system’ including the interdependent subsystems. The ‘footprint’ of one subsystem on the other indicates the interdependency and the influence of one on the other. Processes in each subsystem and the limiting conditions that determine the final capacity of the system is discussed later in the thesis.

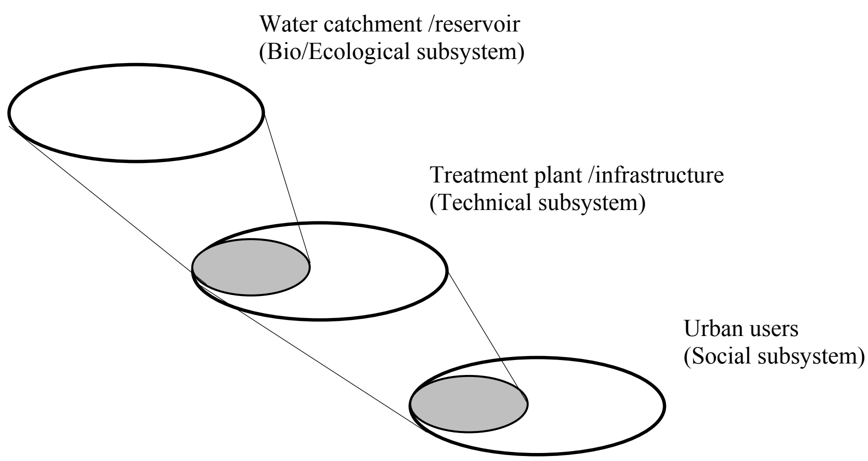


Figure 1.1 – Interdependent water domains as a meta-system (adapted from Barnes *et al.* 2011)

A resilient water supply is a result of successful operations and successful interactions of the processes, even when the system is subjected to pressures.

Considering the main processes of a water supply system, as discussed above, it is clear that the key factors influencing water supply system functionality are, ***water availability***, and the ***quality*** of raw water. The treatment plant capacity; the user population and usage characteristics highly influence these key factors.

There are many factors that influence availability and quality of a water supply system. One of the primary influential factors that affect both water availability and quality is climate change. Climate change influence water availability and quality in different ways. For example, increased temperature due to climate change directly increases evapotranspiration in the catchment and furthermore climate change will increase the frequency and duration of droughts that cause reduction of available water. These factors also cause water quality deterioration. Urban expansion into supply catchments driven by increased populations will strongly affect the availability and quality of water. A detailed discussion about the influence of climate change and populating growth on a water supply system is given in Chapter 2 of the thesis. Although there are other influential factors that affect water availability and quality, climate change and population growth are considered in this study as the primary causes that adversely affect water availability and quality. Therefore, it is critical to identify how climate change and population growth will affect water availability and quality that affect the system resilience.

An accurate analysis of resilience of the system should include consideration of the relationships between the ‘pressures’ (created by climate change and population growth, as considered in this study) and the resilient characteristics of the system that contribute to system output. The main focus of this study was to develop an approach to assess the resilience of the entire water supply system.

A resilience assessment cannot have an exact methodology due to many reasons. Firstly, a resilience assessment must be developed specifically for each system and the pressures it faces. The output of a system may be quantitative but can also be qualitative such as a service which may be difficult to quantify. Accordingly, the parameters to measure system output will differ. Also, the parameters used to assess pressures will vary, depending on the type of pressure. Consequently the exact resilience assessment technique will vary between systems. Variations of potential service delivery levels, both qualitative and quantitative, help to assess the system strengths and capabilities. This project aims to develop a generalized approach to resilience assessment of a water supply system under different pressure scenarios by modelling an existing system and assessing the system capabilities as a way of expressing the resilience of the system.

1.3 RESEARCH QUESTION

It is important for the operators of a water supply system to have a thorough knowledge of the operational boundaries and limits of the system under their control. However, due to variability in system characteristics as well as the operational environment, a water supply system might be expected to operate outside its design parameters from time to time. In such cases where the projected pressures exceed the design pressure limits risk of system failure increases and may be expected. It may be expected that system operators should understand system behaviour beyond the design pressure limit, in order to be able to identify the most appropriate suite of management decisions to avoid functional failure.

Accordingly the research questions were formulated as follows:

- What extent of pressure can the system absorb before reaching the threshold pressure limit?
- What are the optimum levels of pressures at which the early actions are required in order to avoid catastrophic failure of the system?

1.4 AIMS AND OBJECTIVES

Aims

- To identify the characteristics of a water supply system that control the resilience of the system to the pressures of climate change and population growth impacts,
- To identify suitable indicators of resilience to formulate an approach to assess resilience of a water supply system,
- To apply the proposed generic resilience assessment approach to a water supply system in order to investigate relative advantages of using the concept of resilience in the water supply arena.

Objective

The primary objective of the research was to contribute knowledge towards understanding the behaviour of a water supply system under pressures, which is crucial in formulating effective management practices to ensure reliable water supply.

1.5 CONTRIBUTION TO KNOWLEDGE

Past research studies have used the concept of resilience in the field of water supply (Fiering 1982; Li and Lence 2007; Wang and Blackmore 2009) with a view to operationalising the concept for understanding system behaviour and to carry out appropriate management actions. Most of the studies have considered only a single component of a water supply system. This research aims to evaluate the entire water supply system in relation to its ability to supply water under different pressure scenarios.

As a complete water supply system is a complex system, which encompasses subsystems with different characteristics and relationships, the development of a generic approach to assess resilience of a complete water supply system provides a significant contribution to the formulation of effective management practices. Hence, an innovative approach based on this relatively new concept, and considering an entire water supply system, is the primary contribution of this study. Such new knowledge will be useful for understanding the ability of the system to absorb pressure, and the trigger thresholds to avoid catastrophic failure.

Justification for the project

To achieve management goals in complex systems, complex procedures may be required. Uncertainties in relation to the operating environment, such as climate variability and change and increasing demand, further add to this complexity. Depending on climatic conditions, one approach to satisfy the demand placed on a water supply system is to expand the system by building new infrastructure which is a supply side improvement and management process.

A different approach is to understand the system and its components, especially their characteristics and capabilities, in order to manage the relationships between them and to make use of that knowledge to design management strategies to achieve optimum efficiencies. In this way the need to resort to the more commonly adopted option of new infrastructure provision may be delayed or avoided completely. This latter approach presumes that effective decision support systems can be utilised to identify appropriate demand management options.

For the development of a reliable decision support system, an in-depth understanding of system resilience behaviour and critical design limits (trigger points) is required. Knowledge of system resilience allows decision makers time to formulate the most appropriate management strategy when critical trigger points are reached. Identification of the trigger points is key to enhancing efficient management practices. Knowledge of system resilience allows decision makers time to plan for new infrastructure by acknowledging the critical boundaries beyond which the system will not be able to function properly.

The application of the resilience concept to an entire water supply system has not been adequately addressed in the past. The significance of this project is the exploration of a resilience-based approach instead of conventional supply side improvements to infrastructure systems.

1.6 SCOPE

- Only the disturbances from the long-term trend factors of climate change and population growth impacts were considered as ‘pressures’ for the assessment. Service delivery failures due to other reasons (such as sudden technical failures) were not considered.
- Detailed analyses of climate change, population growth and water quality were not carried as part of this study. Relevant data related to climate change and population growth were obtained from appropriate sources.
- Projection of water quality deterioration due to climate change and population growth was not carried as part of this study and not incorporated in resilience assessment. Where relevant, published water quality studies were considered.
- The internal processes of a treatment plant were not analysed.
- Service delivery was considered only up to bulk water supply point. Distribution to consumers was not considered. Therefore, specifications applicable to the water reticulation system were not considered.

- Only a water supply system in which the maximum demand does not exceed the maximum system capacity was considered for assessment.

1.7 OUTLINE OF THE THESIS

The thesis consists of ten chapters. Chapter 1 provides an introduction to the research, aims and objectives and an overview of the project. Chapters 2 and 3 provide a critical review of research literature: Chapter 2 discusses the impact of climate change and population growth on a water supply system, which includes details of how climate change and population growth influence water quality and quantity and also affects the functionality of the system. Chapter 3 provides a critical review of the concept of resilience, the inherent resilience characteristics of a water supply system and a review of indicators, which is the technique used for the evaluation. Chapter 4 discusses and develops the research method and design. Chapter 5 presents the details of the case study area and the selected water supply system. Chapter 6 describes the development of the dynamic model for the selected water supply system. Chapter 7 discusses the development of the set of indicators that are essential for objective evaluation of model simulations. From this the requirements for identification of suitable indicators for resilience assessment were evaluated and a set of indicators are proposed. Chapter 8 discusses different scenarios for model simulation and system behaviour under these scenarios. Chapter 9 presents the analysis of simulated results and also includes a discussion on how system behaviour relates to the surrogate measure of resilience and the usefulness of identifying changed behaviour of the system. Finally, Chapter 10 provides concluding remarks, along with suggestions for further research.

Chapter 2: Climate Change and Population Growth Impacts on Water Supply Systems

2.1 BACKGROUND

Groundwater and surface water are the most common raw water sources for urban potable water supply systems. Surface water sources are relatively easy to access compared to groundwater sources. The availability and quality of surface water is largely dependent on climate conditions. Reliability of climate dependent surface water sources is an issue of concern due to the predicted adverse impacts of climate change on the water environment. For example, Spiller (2008) projected that reliance on climate dependant supply sources in South East Queensland (SEQ), such as dams and weirs would reduce by 20% from 2006 (95%) to 2012 (75%).

The two key issues of climate change and population growth, that exert significant impacts on surface water supply sources, were the focus of this study. Climate change is an issue of growing concern for urban potable water supply due to the predicted changes to surface water quality and quantity. Population growth increases the demand on a water supply system. Furthermore, urbanisation due to population growth may reduce the quality of surface water sources if urban expansion occurs within the supply catchment. This chapter discusses how climate change and population growth can influence surface water quality and quantity, and in turn how this affects potable water supply.

2.2 CLIMATE CHANGE IMPACTS ON WATER QUANTITY AND CONSEQUENT IMPACTS ON SYSTEM FUNCTIONALITY

2.2.1 Overview of climate change

Global climate change and the resulting increased regional climate variability are key issues in the modern world. Global warming, due to increased atmospheric concentrations of greenhouse gases (GHGs) from the burning of fossil fuels, is the main factor that contributes to climate change. The warming of the climate system is unequivocal and the trend over the past 20 years has seen an increase in average global temperature (IPCC 2007) of around 0.4 ^{o}C. Furthermore, it is expected that this trend will continue. This is clearly evident in Figure 2.1, which shows the global annual mean surface temperature anomaly from the year 1860.

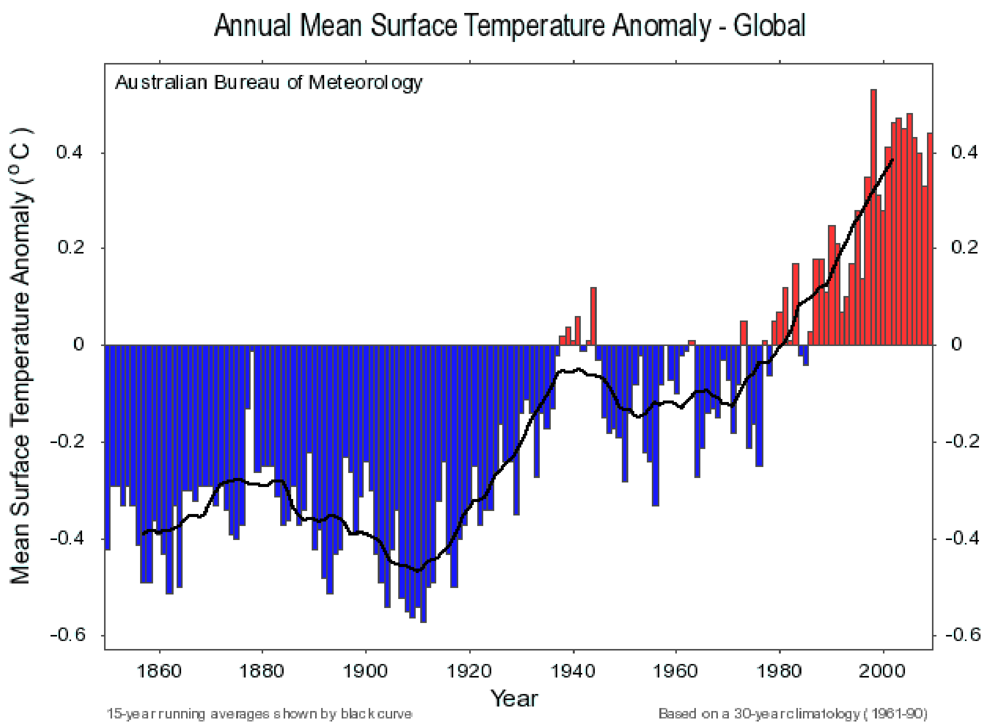


Figure 2.1- Annual mean Temperature Anomaly- Global (adapted from Bureau of Meteorology)

Changes in the atmospheric concentrations of GHGs, aerosols and solar radiation alter the energy balance in the climate system. These are the key factors that influence climate change (IPCC 2007). CSIRO (2006) has pointed out that climate change is an outcome of a chain of processes, which occurs at different stages as illustrated in Figure 2.2.

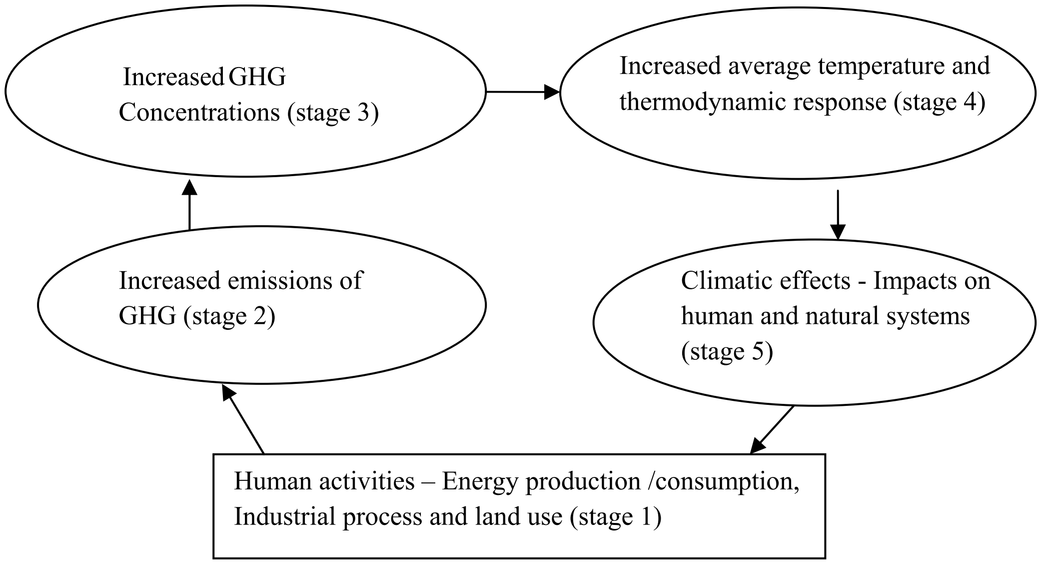


Figure 2.2-Chain of processes linking human activities to climate effects (adapted from CSIRO 2006)

As evident in Figure 2.2, human activities (such as energy production, consumption, industrial processes) and land use practices in stage 1 contribute to the increase in the emissions of GHGs (stage 2) and build-up of GHG concentrations (stage 3). This leads to changes to the atmospheric composition and global patterns of temperature, precipitation and sea level rise (stage 4), which in turn will result in climate impacts on human and natural systems (stage 5). As these processes are linked, they proceed as a chain of processes in a cyclic manner.

As human activities are increasing resulting in increased emissions of GHGs, the severity of projected climate change is also expected to increase. The World Meteorological Organisation (WMO) has developed a range of GHG emission scenarios for future climate change projections (WMO 2013). The WMO describes the emission scenarios as A1, A2, B1 and B2.

The A1 scenario describes a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 scenario describes a very heterogeneous world, in which there is continuously increasing global population and slow per capita economic growth and technological change.

The B1 scenario describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 scenario. However, the B1 scenario rapidly changes its economic structures toward a service and information economy, with reductions in the intensity of material use, and the introduction of clean and resource-efficient technologies. The B2 scenario describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the case of B1 and A1 scenarios.

Depending on the GHG emission scenario, the projections of temperature, rainfall and evaporation for South East Queensland are given in Table 2.1 (Queensland Government 2012). It shows that for all expected scenarios, temperature and evaporation will tend to increase and the rainfall to decrease in the SEQ region. IPCC (2008) also noted that some robust correlations have been observed between temperature and rainfall in many regions.

Table 2.1- Best estimate (50th percentile) projections of temperature, rainfall and potential evaporation for SEQ (adapted from Queensland Government 2012)

	1971-2000 Historical mean	**2030**		**2050**		**2070**	
		Percentage changes					
		Low emission	**High emission**	**Low emission**	**High emission**	**Low emission**	**High emission**
Temperature ^0C	19.4 ^0C	+0.8	+0.8	+1.1	+1.8	+1.5	+2.9
Rainfall %	1135mm	-3	-3	-3	-5	-4	-8
Potential evaporation %	1553mm	+3	+3	+3	+6	+5	+10

Global warming is expected to impact on the water cycle, primarily that will lead to changes in the frequency of extreme climatic events such as droughts and floods (IPCC 2001). The IPCC Third Assessment Report (IPCC 2001) emphasised this fact, highlighting the following as probable changes to water-related systems due to climate change:

1. Increase in heavy precipitation events;
2. Increase in frequency and severity of droughts;
3. Increase in the number of hot days;
4. Increase in water shortages in many water-scarce areas of the world; and
5. Increase in climate variability including heat waves and fewer cold days.

These extreme events are caused by changes to processes in the water cycle. The processes in the water cycle that are vulnerable to climate change are discussed in the next section.

2.2.2 Water cycle

According to the water cycle shown in Figure 2.3, water is distributed in the atmosphere, on land (as groundwater, surface water and snow) and in the ocean in the form of moisture, liquid or solid (snow) phases. The processes of the water cycle consist of evaporation, condensation, precipitation, interception, transpiration, infiltration, storage, runoff and groundwater flow. Global warming is projected to increase the pace of these processes. An accelerated water cycle is expected to lead to increases to the intensity and frequency of floods and droughts (Frederick and Major 1997). These changes can directly influence water storage in catchments that act as the supply sources to a water body. Water storage in a catchment and the climate change impacts are discussed in the next sections.

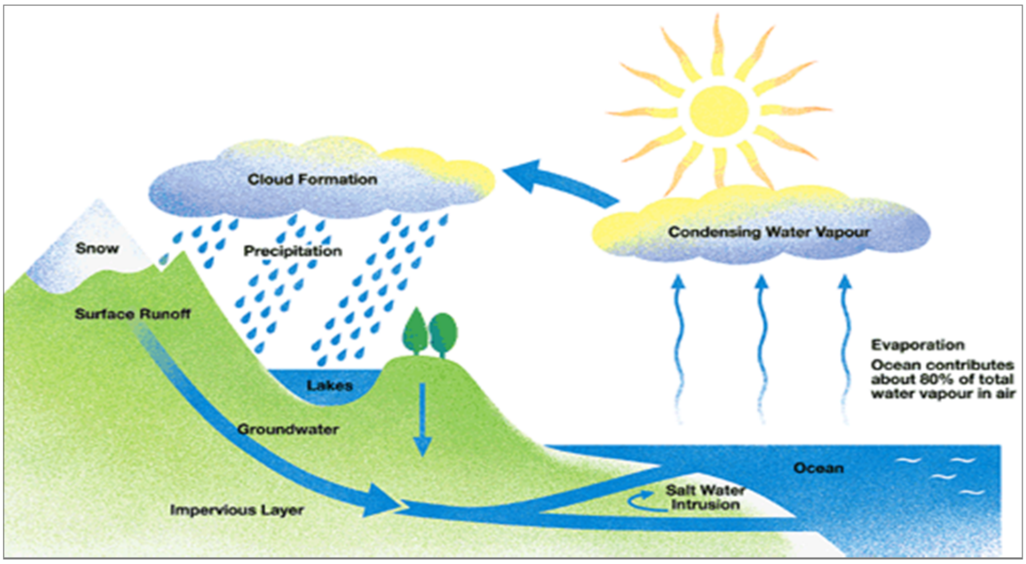


Figure 2.3 -Natural water cycle (Adapted from http: www.sawater.com.au /sawater/ education/ourwatersystems/the+water+cycle.htm)

2.2.3 Water storage in a catchment

The catchment is the land area that drains water into a water body. Kirchner (2009) has noted that the change in water storage over time in a catchment can be expressed by the water balance equation as given in Equation 2.1:

$$\frac{dS}{dt} = P - E - Q \qquad \textit{Equation ....2.1}$$

Where S is the water stored in the catchment measured in unit of depth (mm of water) and P, E and Q are the rate of precipitation, evapotranspiration and discharge, respectively.

In a surface water storage system, the storage reservoir receives a proportion of precipitation through runoff. Precipitation is the main water input source to the catchment as depicted in Equation 2.1 above and also further illustrated by Figure 2.4 below.

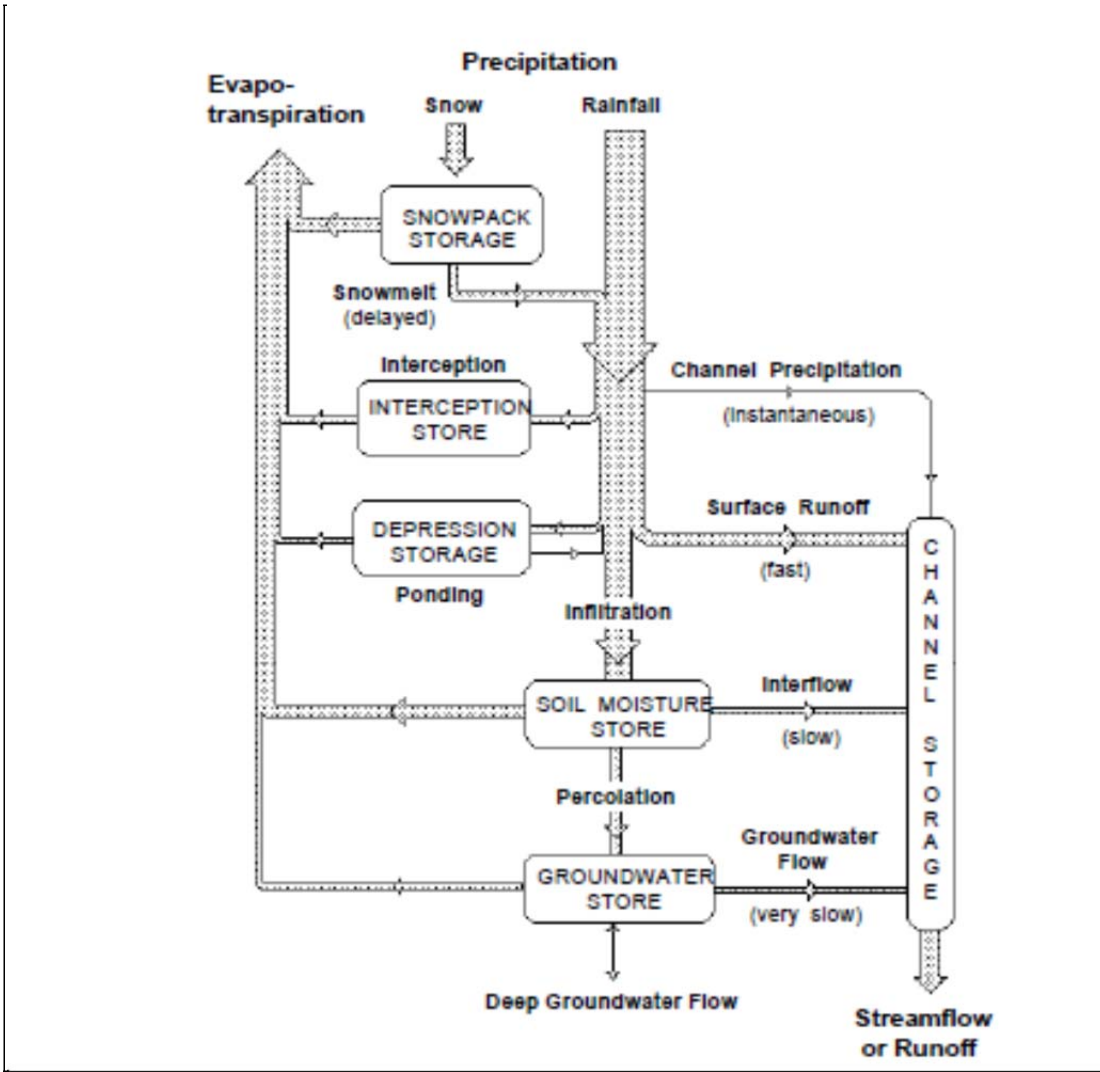


Figure 2.4- Hydrologic processes involved in streamflow generation (adapted from O'Loughlin and Stack 2012)

As evident in Figure 2.4, runoff generation is a complex process, which includes other intermediate and subsidiary processes. These processes are influenced by catchment properties such as topography, area, vegetation cover, land use and soil type that determine the amount of infiltration. Apart from the catchment properties (such as area, topography, vegetation cover), climate parameters such as temperature, evaporation, total rainfall and its intensity (Dunkerley 2012; Wooldridge *et al.* 2001) and other factors such as antecedent dry days (Yair 1990), directly influence the runoff generation process.

Among the factors noted above, rainfall and temperature are the most influential climate parameters that affect runoff into a storage. Noguchi *et al.* (2005) noted for the catchments he studied, that after a dry period, rainwater was mostly retained in the soil and did not produce significant runoff until there was at least 30mm of rainfall. However, they also noted that this rainfall threshold could vary. A range of mathematical procedures have been developed to estimate these thresholds and critical hydrological components such as runoff generation (O'Loughlin and Stack 2012). Long term research and modelling approaches are required for estimation of the changes to runoff generation due to climate change. Currently, very limited research has been undertaken in this area.

2.2.4 Climate change impacts on total water inflow

Many catchment-level hydrologic studies have been carried out to investigate runoff characteristics (for example, Noguchi *et al.* 2005; Wang *et al.* 2011; Vaze *et al.* 2011; Duncker *et al.* 1995; Leitman 2009). IPCC (2008) noted the difficulty of establishing a clear link between river discharge and temperature or precipitation, due to the difficulty in separating out human intervention within a catchment from variations in temperature or precipitation.

Inflow to a surface water storage reservoir is mainly contributed by river discharge for which stormwater runoff is the major contributor. Runoff is defined as the amount of water that is generated by a one dimensional land surface whereas streamflow can be considered as an integral quantity representing the outflow from a large area (Mengelkamp *et al.* 2001). Therefore, variation in runoff will directly influence streamflow variation.

Changes in runoff are the direct result of changes to rainfall and evaporation (Frederick and Major 1997). Consequently, water availability, in the form of inflow, depends on the rainfall and its characteristics, evaporation as well as the antecedent dry period. Hence, climate change may be expected to directly impact the generation of runoff and inflow.

CSIRO (2007) found that projected rainfall decline will result in significant reduction in surface water storage. For example, to-date, Victoria has experienced a 20% decrease in average annual rainfall since the mid 1990s, resulting in inflow reduction of about 40% to the reservoirs. For every, 1% of rainfall decrease, the percentage reduction in inflow is expected double at around 2%, and this factor grows as the drying conditions persist and escalate (CSIRO 2007).

Considering the potential impact of climate change in Australia, modelling studies have indicated significant variation in surface water runoff. For example, according to Chiew and McMahon (2002), average annual streamflow in the North-East Coast and East Coast of Australia could change by between -5 to +15% and ±15%, respectively, by the year 2030; while in Tasmania, the changes are predicted to be ±10% and for Western Australia, a change of –25 to +10% was projected

The risk of significantly lower streamflow poses the greatest pressure to the resilience of water supplies. The annual runoff for South East Australia could decrease by up to 20%; and for Tasmania a potential decrease of 10%. South Australia could experience up to 25% decrease in annual runoff and for Western Australia, a decrease of –25% was projected. These predictions indicate that Southern, South Eastern and Western parts of Australia may generate low annual runoff resulting in water stress in surface water supply systems.

Queensland Water Commission (2010) suggests that by 2030, for areas in western SEQ, evaporation could increase by between 2% and 8% and annual rainfall could reduce by up to 5% due to possible increase in temperature of between 0.8 ^{0}C and 1.2 ^{0}C. Accordingly, an annual reduction in streamflow in the Brisbane River downstream of Mt. Crosby Weir of up to 28% has been projected.

In summary the studies conducted to-date indicate that climate change is likely to have a significant impact on runoff generation which can lead to an increase in pressure on water supply systems.

2.2.5 Sensitivity of seasonal streamflow to climate change

Climate change not only has the potential to affect the total inflow of runoff to a water storage, but also the seasonal runoff distribution (Wang *et al.* 2013). Although a close correlation can be observed between rainfall and runoff volume, the sensitivity of streamflow variation to rainfall variation cannot be so easily predicted. The relationship between streamflow variation and rainfall variation depends on antecedent catchment conditions and rainfall characteristics.

Proportional change in streamflow, as a result of changes in climate variables such as rainfall, was investigated. by Sankarasubramanian *et al.* (2001) who proposed the concept of rainfall elasticity of streamflow. Chew (2006) developed this concept as the nonparametric estimator, $\varepsilon_{p,}$ as shown in Equation 2.2, and used it to consider streamflow in 219 catchments across Australia; and Fu *et al.* (2007) defined this concept as '*climate elasticity of streamflow'*.

Rainfall elasticity of streamflow

ε_p = median $\left(\frac{Qt-\bar{Q}}{Pt-\bar{P}} \; \frac{\bar{P}}{\bar{Q}} \right)$ *Equation……….2.2*

Where

Pt and Qt are rainfall and streamflow at a given time

$\bar{P}$ and $\bar{Q}$ are mean annual rainfall and streamflow respectively.

Of the 219 catchments investigated by Chew (2006), more than 70% of the catchments had elasticity of 2-3.5%. This means, a 1% change in mean annual rainfall will result in a change in mean annual streamflow of between 2% and 3.5%. Sankarasubramanian and Vogel (2003) used this equation to document the rainfall elasticity of streamflow for 1,337 catchments in the USA and found that a 1% change in rainfall resulted in a 1.5- 2.5% change in catchment runoff. These results confirm that the rainfall-runoff relationship does not always follow a linear pattern. High streamflow elasticity means large variations in streamflow due to small variations in rainfall. Hence, high streamflow elasticity leads to low resilience of the water supply system because a small rainfall decrease will result in a large reduction in water inflow to a storage reservoir.

Although change to rainfall is the main influential factor, temperature change can also have a significant impact on streamflow changes. Higher temperatures tend to reduce streamflow. Fu *et al.* (2007) reviewed Equation 2.2 to study the streamflow-precipitation-temperature relationship by incorporating temperature variations as given in Equation 2.3. Equation 2.3 can be used to assess the combined effects of rainfall and temperature changes on the hydrologic regime at catchment scale. Therefore, for any given rainfall and temperature scenario, Equation 2.3 can be used to estimate the annual streamflow response.

$$\epsilon p, \delta t = \left(\frac{Qt\,, \delta t - \overline{Q}}{Pt, \delta t - \overline{P}} \; \frac{\overline{P}}{\overline{\overline{Q}}} \right) \qquad \text{Equation ....2.3}$$

Where Pt and Qt are rainfall and corresponding streamflow

$\overline{P}$ and $\overline{Q}$ are mean annual rainfall and mean annual streamflow

δt = $(T - \overline{T})$ which is the temperature departure and T is the temperature at a given time and $\overline{T}$ is the mean annual temperature

The investigations by Fu *et al.* (2007) revealed that temperature is an important influential factor in relation to streamflow generation showing that a 1.5^{0}C increase in mean temperature for the Spokane River basin in USA resulted in a 20-30% reduction in streamflow when compared to expectations for an unchanged mean temperature. For example, for unchanged mean temperatures, a 30% increase in precipitation resulted in a 50% increase in streamflow. However, for 1.5 increase in mean temperature and a 30% increase in precipitation streamflow only increased by between 20% and 30. Therefore, the reduction of streamflow can be expected as a specific consequence of temperature increase.

Wang *et al.* (2013) further demonstrated the sensitivity of runoff to precipitation and temperature using a model simulation study based on the Kuye River catchment in the Loess Plateau in China for 28 different combinations of precipitation changes of $\pm 30\%, \pm 20\%, \pm 10\%$, 0% and temperature changes of +3^{o}C,+2^{o}C,+1^{o}C and 0^{o}C (Figure 2.5) This Figure shows that for scenarios with no change in temperature (0^{o}C), but with increases in precipitation of 10%, 20% and 30%, annual runoff would increase by 17.8%, 36.9% and 57.1%, respectively for each increase in precipitation. In comparison, for scenarios with no change in precipitation, but with increases in temperature of 1^o, 2^o and 3^{o}C, annual runoff would decrease by 4.0%, 7.8% and 11.4%, respectively. Hence, runoff can be expected to be more sensitive to changes in precipitation than to changes in temperature. It is noted that the effect of temperature increase on runoff is non-linear

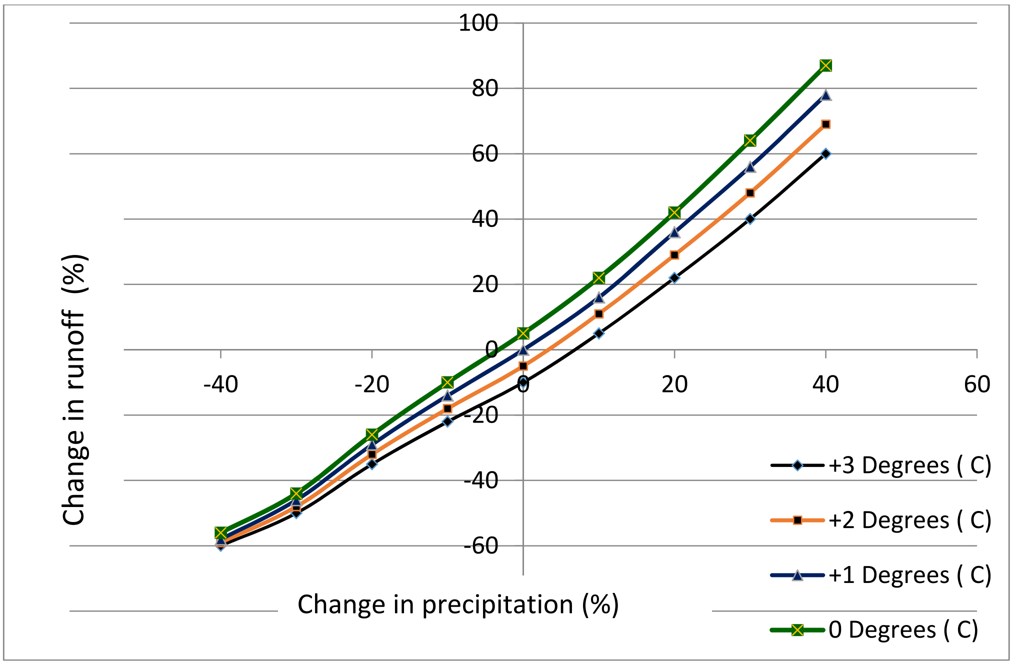


Figure 2.5 – Responses of annual runoff in the Kuye River catchment to climate change (adapted from Wang *et al.* 2013)

Generally, it can be expected that an increase in precipitation results in an increase in streamflow, or in other words, the elasticity of streamflow is positive. However, Fu *et al.* (2007) noted that climate elasticity of streamflow can be negative, i.e. precipitation increase resulting in a decrease in annual streamflow under the following circumstances:

- Small precipitation increase combined with a large temperature increase.
- Small precipitation decrease combined with a large temperature decrease.

In the first instance, the large temperature increase and small precipitation increase may result in reduced streamflow generation, due to more losses occurring from evapotranspiration resulting in reduced contribution to streamflow generation. Conversely, in the second instance, the reduction in streamflow due to decrease in precipitation could be compensated by a reduced amount of losses from other processes such as evapotranspiration and a consequentially greater contribution to runoff generation.

Another important observation in the study by Fu *et al.* (2007) was that the volume of streamflow generation is more sensitive to decreasing precipitation than increasing precipitation. In comparison, for the Spokane River basin in USA, the climate elasticity of streamflow was 1.1-1.4% for precipitation increase and 1.6% for precipitation decrease. Therefore, predictions of future precipitation decrease will be a critical issue for water supply systems.

A range of parameters other than temperature and precipitation can also influence streamflow elasticity. Yang and Yang (2011) carried out a study on 89 catchments in China to investigate the elasticity of streamflow for a range of parameters including precipitation, temperature, net radiation, wind speed at 2m above ground and relative humidity. The results showed that precipitation was the most influential parameter for runoff generation. Temperature and runoff were negatively correlated and other parameters investigated were not as significant as precipitation and temperature.

As discussed in the previous sections, it is clear that climate change has a significant impact on water inflow to the storage reservoir and in turn, low inflow creates the stress of ‘low water availability’. As all the processes in a water supply system depend on water availability, it will influence the functionality of the entire system. Therefore, climate change has the potential to influence the extent and severity of failure of the system particularly through decrease in rainfall.

2.3 CLIMATE CHANGE IMPACTS ON WATER QUALITY

In addition to quantitative impacts, surface water quality is also likely to be affected by climate change. Qualitative changes to raw water are of critical importance to water supply systems due to their influence on the water treatment process and treatment plant capacity. The treatment plant can operate to its full potential only if raw water supply remains within a defined range of treatable quality.

The quality of drinking water is measured in terms of its microbiological quality, physical quality, chemical quality and radiological quality (ADWG 1996). Microbiological quality is determined by the number of pathogenic (disease causing) microorganisms such as bacteria, viruses and protozoa present in water. Physical quality is determined by measurable physical characteristics such as true colour, turbidity, total dissolved solids (TDS), temperature, taste and odour. Chemical quality is determined by concentrations of inorganic and organic compounds and radiological quality is the amount of radiological contaminations in water.

Among the above four categories, physical and chemical quality are most likely to be affected by climate change. Both, physical quality and chemical quality are influenced by ambient (air) temperature and extreme hydrological events that can occur due to climate change (Delpla *et al.* 2009).

Long periods of high temperature can lead to thermal stratification especially in deep water storage reservoirs. Thermal stratification is the separation of the water body into three main layers; epilimnion (top layer), metalimnion or thermocline (middle layer and hypolimnion (bottom layer). The separation is caused due to different water densities with different temperature. Cold water is denser than warm water and the epilimnion generally consists of water at relatively high temperature and hence is not as dense as the water in the hypolimnion.

Changes in water temperature can directly influence temperature-dependent water quality parameters including dissolved oxygen, pH and microbial activity (Park *et al.* 2010). The level of dissolved oxygen (DO) in water is one of the most important parameters in determining water quality, because oxygen is an essential element for aerobic life. DO depends on the water temperature, dissolved salts, atmospheric pressure and suspended matter (Ibanex *et al.* 2008). Higher water temperature decreases the amount of dissolved oxygen (Ducharne 2008). Furthermore, reduced oxygen levels under warmer conditions will cause natural self purification processes in water bodies to slow down (Miller 2008). This will adversely affect other organisms that require oxygen for survival, resulting in significant pollution problems in water bodies.

The potential for increase of carbon, nitrogen and phosphorous concentrations in water is also greater at high temperatures due to their release from soil organic matter (Delpla *et al.* 2009). Increased nutrients lead to eutrophication (rapid growth of phytoplankton resulting in algal blooms) due to excessive plant growth in water bodies as a result of increased inputs (O'Sullivan 1995). Hence, warmer conditions promote the eutrophication process in the presence of increased amount of nutrients.

Algae exposed to high concentrations of nutrients grow vigorously and complete their life cycle quickly. A storage reservoir with a large amount of dead algae will have low oxygen content, since dissolved oxygen is consumed as the algae decompose. Although eutrophication occurs as a result of complex interactions between nutrient availability, light conditions, temperature, residence time and flow conditions (Jeppesen *et al.* 2005), climate change may be expected to provide the conditions to enhance the eutrophication process. Therefore, increased average temperature when combined with decreased rainfall, is likely to result in increasing risk of eutrophication and potentially cause blooms of cyanobacteria (blue-green algae).

Apart from the temperature effects on surface water quality as discussed above, the other influential factor in relation to water quality is the changes to the way rain falls – the rainfall parameters. Transportation of solids, due to increased runoff, contributes to the degradation of surface water quality. Colour, turbidity, total dissolved solids, taste and odour are directly influenced by the amount of transported sediments and organic material in the water body. The amount of these pollutants in a water body is strongly influenced by the pollutant wash-off process. Wash-off is the process by which pollutants, built-up on a surface during the preceding dry period, are flushed with the runoff into the receiving water. Goonetilleke and Thomas (2003) noted that during storms with high total rainfall, the total load of pollutants washed off was proportionately larger than for storms with less rainfall.

When the water level is low in a water body such as during a drought, exposed shorelines and sedimentary deposits risk being eroded during heavy rainfall events resulting in the further accumulation of dissolved organic matter, nutrients, trace pollutants and pathogens in water bodies. Hence, heavy rainfall events followed by drought creates a favourable environment for increasing the pollution in a water body. Climate change is projected to increase the frequency and duration of droughts and consequently may be expected to result in the deterioration of water quality in water storages Delpla *et al.* (2009) illustrated the combined effects of climate change and urbanisation on water resources and the impact on water quality as shown in Figure 2.6.

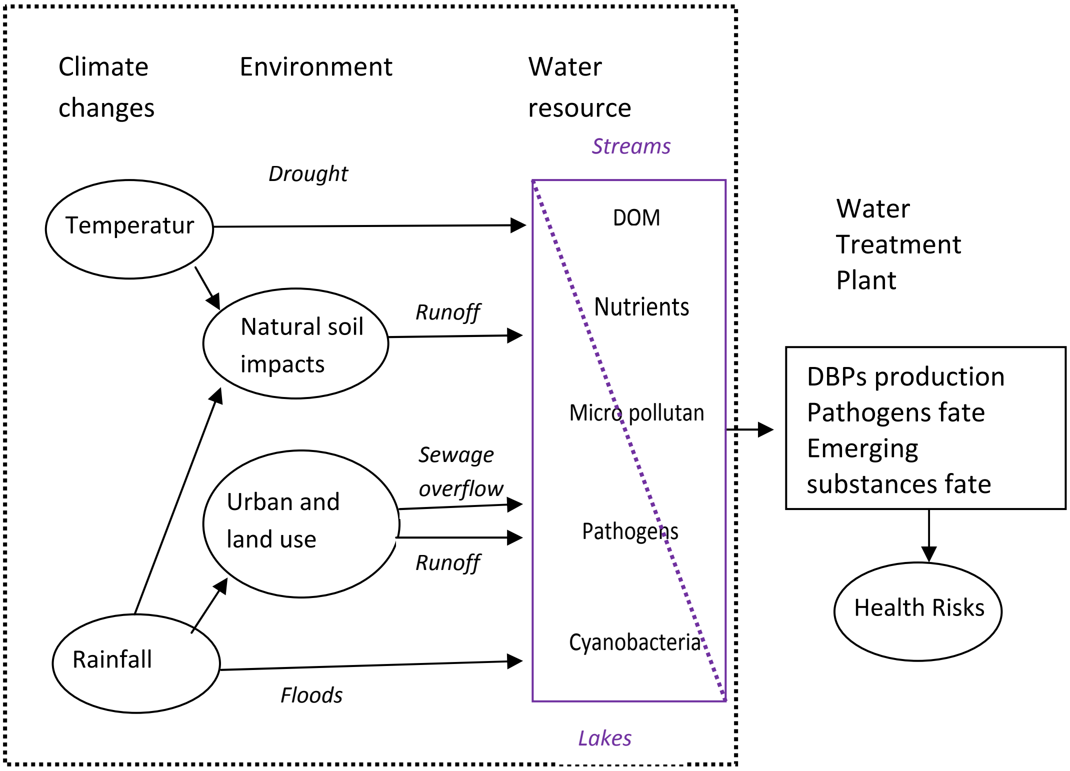


Figure 2.6 -Climate change and urbanisation impacts on water resources and drinking water quality (adapted from Delpla *et al.* 2009)

Figure 2.6 shows that the main consequences of climate change, changes in temperature and rainfall parameters, will affect the environment causing floods and droughts**.** Floods and droughts change the water quality in water bodies due to increased inputs of dissolved organic matter, nutrients, trace pollutants and pathogens as discussed in Section 2.3. Some of the trace pollutants (micropollutants) may also include newly emerging pollutants, which can be defined as any synthetic or naturally occurring chemical or any microorganism not commonly found in the environment. They are very mobile in the environment and difficult to remove (Verliefde *et al.* 2007).

Hence, it may be concluded that low rainfall and extended droughts due to climate change will reduce water storage (availability) in a water supply system and also lower the water quality. Increases in temperature will also contribute to reduced water availability and water quality.

The two subsystems, the storage reservoir and the treatment plant, will be the subsystems most affected by these impacts of climate change. The adverse effects on these subsystems will affect the overall performance of the water supply system. Taking these facts into account, the main issue is how far the system can resolve these issues of its own without causing supply limitations under these adverse impacts.

2.4 POPULATION GROWTH IMPACTS ON WATER DEMAND AND QUALITY

The direct impact of population growth on a water supply system is linked to water demand. Increasing demand (pressure) leads to the increase in the rate of reservoir drawdown and thereby reducing water availability for future need (increasing stress). However, where a particular system is concerned, there is a maximum supply limit in terms of the volume that the system is capable of supplying at an acceptable quality. The average population that a system can reliably supply is calculated based on the maximum supply volume and a fixed (average) per capita consumption level. In this way the maximum population that a system can service is an attribute of the system.

Population growth can alter the time frame in which the system reaches its maximum output limit, which is explained below for the SEQ Water Grid, assuming no changes to the system. The SEQ Water Grid is the water supply system that supplies potable water to South East Queensland. Figure 2.7 illustrates the trend in demand increase for the SEQ region and expected supply from the SEQ Water Grid. Level of Service yield means the volume of water that can be supplied by the SEQ Water Grid on average per year.

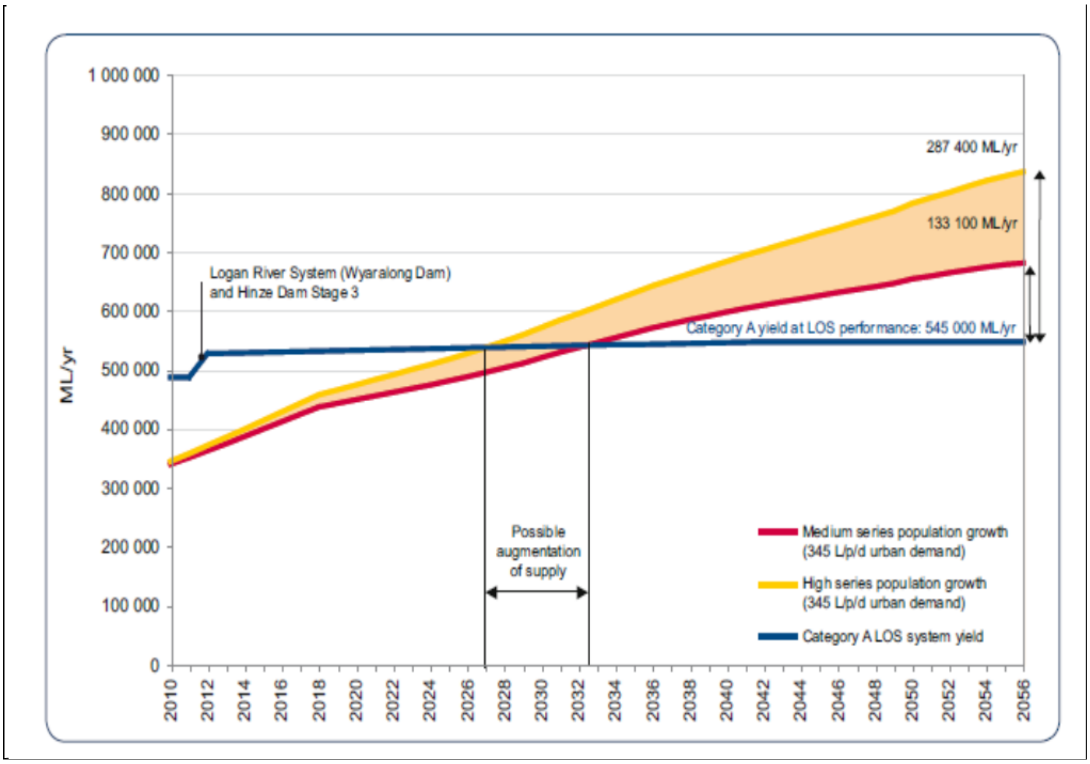


Figure 2.7 - Impact of different population scenarios and consumption for the SEQ Water Grid (adapted from QWC 2010)

Figure 2.7 shows that the category A (high priority) Level of Service (LOS) yield in the SEQ Water Grid increased from 485,000 ML/year to 545,000 ML/year after completion of the Logan River system and Hinze Dam Stage 3 in 2012. QWC (2010) notes that the SEQ Water Grid will reach its LOS yield by 2027 (for high population growth) with a consumption level of 345 L/p/d (refer to yellow line in Figure 2.7). However, it will not reach this limit until 2032 under medium population growth and consumption level of 345 L/p/d (red line in Figure 2.7). This difference in time frame to reach the maximum supply potential of the system is the result of different population growth rates.

Degradation of water quality is the other impact of population growth on a water supply system. Urbanisation within the supply catchment due to population growth, risks increases in pollutant load to the catchments. Therefore, increased loads of pollutants may enter water bodies at a higher rate through urban stormwater runoff. Also, urban expansion within the catchment will create more potential point and non-point pollutant sources, such as street surfaces, industry, construction and demolition, sources of material corrosion, vegetation input, spills and erosion (Goonetilleke and Thomas 2003; Yang et al 2007).

Major pollutant categories found in urban stormwater include suspended solids, heavy metals, polycyclic aromatic hydrocarbons (PAHs), nutrients and a wide range of particulate matter (Aryal *et al.* 2010). Byrne and DeLeon (1987) in their study found high concentrations of heavy metals (such as barium, copper, nickel, lead and zinc) in water bodies close to highly urbanised areas compared to less urbanised areas. Sanger *et al.* (1999) noted that sediments in creeks in industrial areas in South Carolina had significantly higher concentrations of PAHs and other organic pollutants compared to creeks in suburban and forested catchments. Hence, the consequence of urbanisation is the risk of higher rates of pollution, as illustrated by indicators such as pH, conductivity, dissolved oxygen (DO), turbidity, salinity, total nitrogen (TN), total phosphorus (TP) and chemical oxygen demand (COD) (Yang *et al.* 2007).

The presence of heavy metals and hydrocarbons in urban runoff is of concern as they do not readily degrade in the environment, and bioaccumulate to toxic levels (Herngren *et al.*2005). Suspended solids contribute to increase in turbidity in water. High concentrations of nutrients lead to the formation of algal blooms. Such eutrophic systems that support large algal populations reduce the clarity of water and degrade its colour (Wilson 2010).

As discussed in Sections 2.3 and 2.4, it is evident that both climate change and population growth can contribute to degrade surface water quality. Minor quality variations do not affect the level of final service delivery as the treatment plant acts as a restoring element within the complete system. However, during a major quality deterioration incident, the treatment plant may not be able to treat at the same rate, resulting in a low supply rate. Therefore, the capacity of the treatment plant to treat low quality water and maintain output will enhance the ability of the system to maintain functionality without leading the system to reach a critical threshold.

2.5 CONCLUSIONS

Water quantity and quality are the main concerns of a water supply system. Water quality and quantity issues tend to push a water supply system towards the critical supply thresholds, below which the system will not function adequately to meet service standards.

Climate change is an issue of growing concern for urban potable water supply systems. Increasing trends of temperature and changes to rainfall patterns are common consequences of climate change that affect natural and socio-ecological systems, both directly and indirectly. Although human activities largely contribute to global warming, for the purpose of this study this is considered an uncontrollable phenomenon.

Projections of climate change impacts indicate that rainfall will decrease in some regions. Sensitivity of streamflow generation to decreasing rainfall is greater than that of increasing rainfall. Studies show that 1% decrease in rainfall will result in a greater decrease in streamflow. Regarding surface water quality, physical and chemical quality parameters are mostly affected by climate change. Therefore, climate change will be a critical issue in future urban water supply.

Population growth is another issue that will create pressure on water supply systems. Population growth will increase water demand and also contribute to the degradation of water quality due to the contribution of pollutants at an increased rate to water catchments and the creation of additional pollutant sources as a result of urbanisation. Low quality of water can lead the system to reduce its maximum supply potential. The criticality of water quality deterioration and quantity reduction in a water supply system are the possible failure scenarios of the system striving to maintain service standards.

Chapter 3: Resilience: Concept, Method of Evaluation and Indicators

3.1 BACKGROUND

Water supply systems are highly influenced by human activities and changes to the natural environmental. Climate change, coupled with increasing demand from expanding global populations and their current consumption patterns for water, are pushing water supplies beyond levels that can be sustained. To achieve the sustainable management of water supply, a key property to consider is its resilience (Carpenter *et al.* 2005). Folke *et al.* (2002) noted that resilience theory provides a conceptual foundation for sustainable development.

The fundamental definition of resilience, as noted by the Oxford English dictionary is, 'the ability to recoil or spring back into shape after bending, stretching or being compressed' or an 'ability to withstand or recover quickly from difficult conditions'. The focal interest of this study is to explore the concept of resilience in the context of water supply management.

This chapter provides a review of the concept of resilience and the usage of indicators as a means of evaluating system resilience. Accordingly, the definitions of resilience, key concepts, different forms of application, and their relevance to a water supply system are discussed in detail. Furthermore, the types of indicators or resilience and how these indicators have been used in similar studies is also discussed. The primary interest was on the identification of the inherent characteristics of a water supply system in relation to the resilience of the system under the pressures of climate change and population growth.

3.2 RESILIENCE – FUNDAMENTAL DEFINITIONS

Gordon (1978) suggested, in a purely mechanical sense, that the resilience of a material is the quality of being able to store strain energy and deflect it elastically under a load without breaking or being deformed. Richard *et al.* (2003) referred to the Latin word *resilio* in defining resilience to mean 'jump back'. Many other similar definitions of resilience can be found in the literature. Some of the definitions relevant to this study are given below;

- *Resilience is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables* (Holing 1973).
- *Resilience is the amount of disturbance that a system can absorb without changing state* (Gunderson 2000).
- *Resilience is the measure of the speed of a system's return to equilibrium following perturbation (*Brock *et al*. 2002).
- *Resilience is the potential of a system to remain in a particular configuration and to maintain its feedback and functions, and involves the ability of the system to reorganize following disturbance-driven change* (Walker *et al.* 2002).
- *Resilience is the buffer capacity or the ability of a system to absorb perturbations, or the magnitude of disturbance that can be absorbed before a system changes its structure by changing the variables and processes that control behaviour* (Adger 2000).
- *Resilience is the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change (IPCC 2007).*

Although there is no universally accepted standard interpretation to explain the concept of resilience, there is a commonality in its general meaning that highlights the specific ability to overcome disturbance and to return to a specified state. As it is an essential characteristic in many disciplines, numerous forms of resilience have been defined in the literature.

3.3 DIFFERENT FORMS OF RESILIENCE

The concept of system resilience emerged from ecology in the 1960s and early 1970s (Folke 2006). Madni and Jackson (2009) illustrated the different forms of resilience as applicable to different disciplines as outlined in Table 3.1.

Table 3.1 – Forms of Resilience (adapted from Madni and Jackson 2009)

Resilience type	Description
Ecological Resilience	(1) Rate at which a system returns to a single steady or cyclic state following a perturbation or transient. (2) A measure of the amount of change or disruption that is required to transition a system from being maintained by one set of mutually reinforcing processes and structures to a different set of processes and structures.
Economic and Business resilience	Ability of a local economy to retain function, employment and prosperity in the face of perturbation caused by shock of losing a particular type of local industry or employer.
Industrial and Organisational resilience	Ability of an industry/organisation to strengthen the creation of robust, flexible processes in a proactive fashion.
Network resilience	(1) Ability of a network to provide and maintain an acceptable level of service in the face of faults and challenges to normal operations. (2) The acceptable level of service pertains to being able to access information when needed, maintain end-to-end communications and ensure smooth operation of distributed processing and networked storage.
Psychological resilience	(1) The capacity of people to cope with stress and catastrophe (2) Psychological resilience is often contrasted with “risk factors.”
Socio-ecological resilience	(1) Resilience controlled by slowly changing variables. (2) A function of investments in natural human, social and physical capital.

The interpretation of resilience varies depending on the context and the field of application. Due to the wide diversity of application and interpretation, it is noteworthy to mention that the identification of operational characteristics of resilience is very important for resilience-related studies. Therefore, the discussion in this chapter focusses on operational resilience characteristics of a water supply system based on the meta-system concept introduced in Chapter 1.

Dekker and Hollnagel (2006) interpreted systemic resilience as the ability of a system to recognise, absorb and adapt to disruptions that fall outside a system's design base. A similar definition by Cox (2008), suggests that a resilient system has a highly adaptive capacity in the face of disturbances and is able to withstand disturbances without a decline in critical function. Kjeldsen and Rosbjerg (2004) quoting Hashimoto et al. (1982) suggested that resilience is a measure of how fast a system is likely to return to a satisfactory state after the system had entered an unsatisfactory state. These interpretations provide a range of key operational characteristics of resilience, which are directly relevant to the study of water supply systems.

3.4 CHARACTERISTICS OF RESILIENCE

In the different forms of resilience noted above, the common characteristics of resilience can be identified. Vugrin (2010) identified three fundamental and essential characteristics of resilience:

- absorptive capacity (the degree to which the system can absorb the impacts of perturbation without changing state or losing function);
- adaptive capacity (the degree to which the system is capable of self re-organisation for recovery); and
- restorative capacity (the ability of the system to be repaired).

As interpreted by Wang and Blackmore (2009), the absorptive capacity infers the system's ability against crossing a critical threshold and the restorative capacity explains the response and recovery of the system after a failure event. These characteristics facilitate successful functionality under pressure, whether it is a socio-ecological or technical system. Table 3.2 provides a more detailed coverage of the application of the resilience concept related to the above-mentioned fundamental characteristics.

Table 3.2 – Comparisons of attributes of Resilience (adapted from Wang and Blackmore 2009)

Attributes	Ability to withstand regime change	Ability to response/recovery	Adaptive capacity/management
Definition	Magnitude of disturbance that can be absorbed without flipping into an alternative state	Speed or rate of system recovery after disturbance	Ability to pre-empt and avoid major mishaps in institutions
Objectives	Positioning the system in a favourable regime (original or alternate)	Returning the system to an operational status in the original or alternate regime	Reducing incident and accident occurrences and impact if occurred in institutions
Emphasis	Persistence, change, unpredictability	Efficiency, constancy, predictability	Proactively monitoring the effects of existing management and operational approaches
Controls & factors	Slow and fast variables	Slow and fast variables	Management and operational variables
Concern	Small and large disturbance	Concentrating on low frequency, high consequence disturbance	Disturbance originating from organisational management and operations
Assessment	Mainly qualitative	Mainly quantitative	Rules and operational procedures

However, others have broadened the range of characteristics associated with the concept of resilience to include persistence, robustness, and efficiency as well as the ability to absorb pressure, adaptability and recovery, (Holling 1973; Vugrin 2010; Wang and Blackmore 2009; Wang *et al*. 2009). Analysis of this range of overlapping characteristics has been central to the development of the science of resilience engineering. Madni and Jackson (2009) have stated that resilience engineering is based on four key pillars. They are; *disruptions, system attributes, methods* and *metrics*. These four are interrelated. For example: a system can be affected by *disruptions,* which can be natural or anthropogenic, external or systemic, single-agent or multi-agent and short lived or continuing. *System attributes* are the characteristics or properties of the system such as system functionality, system complexity, organisational infrastructure, system performance and system breakdown structure. *Methods* are associated with the functionality of the system and include conventional risk assessments, safety measures, utility-cost trade-offs, integrative/holistic methods and ongoing proactive risk management processes. Finally suitable *metrics* need to be identified to assess resilience, Accordingly, system resilience can be illustrated as given in Figure 3.1 below.

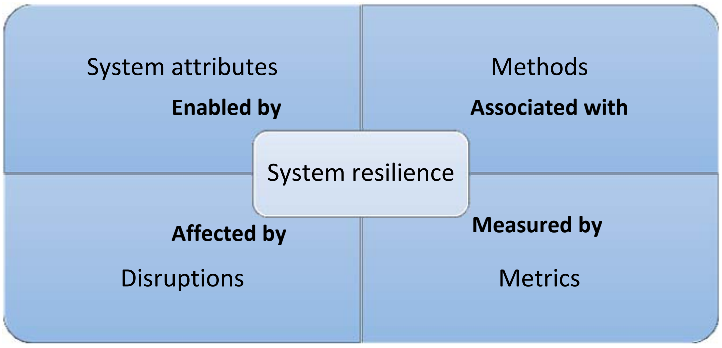


Figure 3.1 – System resilience (adapted from Madni and Jackson 2009)

In the case of complex systems, failures are not uncommon. In resilience engineering, failure is seen as the inability to perform the necessary adaptations to cope with real world complexity, rather than as a breakdown or malfunction (Madni and Jackson 2009). A resilient system consists of avoidance, survival and recovery features that will help to continue operation under pressure. Therefore, a resilient system should be able to change to suit the changing environment. Success depends on the ability of the system to adapt to changes and new developments. This ability will reduce the risk of failure due to the pressures acting on the system.

Based on the literature, the two fundamental system capabilities; '**ability to withstand pressure**' and '**ability to recover from disturbance'** have been adopted as the operational characteristics for this study. In order to possess these abilities, a system should have the capacity to change and adapt to varying conditions. The ability to change system properties can be explained as the dynamic capacity. A system subjected to pressure, needs to activate new or redundant resources within the system to resist the disturbances and to withstand the pressure or to reorganise in order to recover. This activation process of the system is facilitated by the dynamic properties (systemic properties that have the capability to change) of the system. Therefore, in order to evaluate the level of systemic resilience, the dynamic properties of the system need to be identified.

3.5 KEY CONCEPTS OF RESILIENCE RELATED TO A WATER SUPPLY SYSTEM

3.5.1 General and specific resilience

Resilience "*of what*" and "*to what*" are two essential terms required in order to define the resilience of a specific system. These two terms explain the context and the pressures applied to a system. For example, the expression 'resilience of a water supply system' does not clarify the type of pressure to which the system is subjected. Therefore, unless resilience '*to what'* is defined, the term is generalised.

When resilience '*to what'* is clearly explained, it becomes a specific enquiry. For example, the expression, 'resilience of a water supply system *to climate change'*, explains that climate change is the pressure being applied to the system. The significance of explaining specific resilience is that the same system may have different degrees of resilience to different types of pressures (Haimes 2009). Hence, for a complex system, the question of the resilience of any infrastructure is not answerable, unless resilience '*to what'* is also specified.

3.5.2 Ecological and engineering resilience

Two important distinctions of resilience are ecological and engineering resilience. Systemic resilience of an ecological system is primarily focused on different aspects of stability (Holling 1973). Holling (1973) characterised stability as persistence of a system near or close to an equilibrium state. The concept of ecological resilience presumes the existence of multiple stability domains and the tolerance of the system to perturbations that facilitate transformations between different states. Accordingly, ecological resilience refers to the width or limit of a stability domain and is defined by the magnitude of disturbances that a system can absorb before it changes states (Ludwig *et al.*1996).

Holling (1996) noted that engineering resilience is based primarily on efficiency for returning to the equilibrium or steady state following a perturbation. Hence, ‘engineering resilience’ can be defined as the return time to equilibrium. It is assumed that only one equilibrium or steady state exists or if other operating states exist, they should be avoided. Gersonius (2008) refers to engineering resilience in terms of the behaviour of a system in the immediate vicinity of a stable equilibrium.

Schaffer al. (1993) used the heuristic of a ball and a cup to highlight alternate equilibrium states so that ecological resilience and engineering resilience can be distinguished. The ball (Figure 3.2) represents the system state and the cup represents the stability domain. Equilibrium exists when the ball sits at the bottom of the cup and disturbances shake the ball to the transient position within the cup. Engineering resilience refers to characteristics of the shape of the cup, as the slope of the sides dictates the return time of the ball to the bottom. Ecological resilience suggests that more than one cup exists, and is defined as the width at the top of the cup. Implicit in both these definitions is the assumption that resilience is a static property of systems. That is, once defined, the shape of the cup remains fixed over time. However, stability domains are not always static. The characteristics of dynamic and variable domains are discussed in the next section.

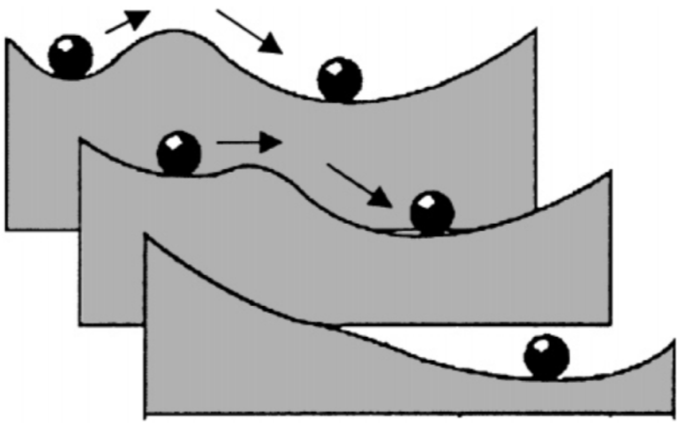


Figure 3.2- Ball and cup heuristics of system stability. Engineering resilience is determined by the slopes in the stability landscape whereas ecological resilience is described by the width of the cup (adapted from Gunderson 2000)

3.5.3 Attractor basin representation of alternate regimes and thresholds

Dynamic stability domains can change their configuration by allowing the system to exist in alternate states. When a resilient system is under certain pressures, the system tries to withstand the pressures by changing its operational configuration.

However, the term “alternate state” can be confusing unless it is well defined. The state of the system at any time can be defined by the values (amount) of the variables that constitute the system (Resilience Alliance 2011). For example, if a system state is defined by the amounts of grass, shrubs and livestock, different combinations of these variables will define the state of the system at that time. Therefore, a resilient system copes with pressures by changing its configuration. This configuration change allows the system to stay in an alternate state with the same functionality. The change in configuration of a resilient system to become a stable system can be visualised by using the metaphor of basins of attraction in a stability landscape as given in a three dimensional “ball in the basin” representation illustrated in Figure 3.3 (Resilience Alliance 2011).

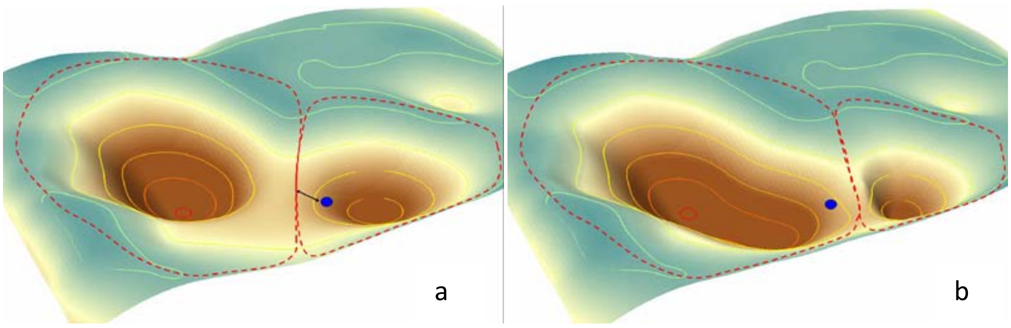


Figure 3.3- The "ball-in-the-basin" representation of resilience (adapted from Resilience Alliance 2011)

Figure 3.3 (a) and (b) represents two configurations of a system. A basin represents a “regime”. Alternate regimes are separated by “thresholds”, which are system boundaries that separate one state from the other. The ball represents the “state” of the system. The ball (state) crossing the regime indicates a change of system state. The most stable state is when the ball is at the lowest position of a basin. Therefore, the ball always tries to move to the lowest elevation. This can happen either by moving the ball across the threshold (changing the state) as shown in Figure 3.3 (a) or by changing the shape of the basin (changing the configuration without changing state) as shown in Figure 3.3(b). A resilient system is one that does not tend to change the state. The change of state indicates the inability of the system to withstand the pressure that pushes it towards a different state. Therefore, the resilient system changes the configuration as illustrated in Figure 3.3(b), without changing the state to move to the most stable state.

A real world example of changing the state occurred in Florida Bay in the early 1990s in which the bay shifted from an oligotrophic state to a turbid state dominated by phytoplankton blooms. This shift resulted in changes in characteristics and processes such as water clarity, primary production, nutrient cycling and food webs (Groffman *et al*. 2006).

Understanding thresholds and critical limits is also essential for managing for resilience (Garmestani and Benson 2013; Walker *et al*. 2009). Therefore, in order to assess the level of resilience of a system, it is necessary to relate the system state to the thresholds. Accordingly, in the current research study the potential output levels of the water supply system were related to the failure thresholds. Smith *et al*. (2009) defined thresholds as upper and lower level indicators expressed as management goals that represent the current understanding of the conditions of a system. They further noted that when a threshold is reached, management actions can be applied and thresholds can be recalibrated in an adaptive manner, if necessary. When more than one variable is involved in setting the threshold, there can be different results from different combinations of variables. In such cases, identification or setting of thresholds is difficult.

With respect to the above "ball-in-the basin" representation of resilience, the Resilience Alliance (2011) has pointed out that resilience assessment is about understanding the following:

- The state of the system the ball is in, in relation to the basin's boundaries;
- Navigation to either avoid going into an undesirable basin, or to go from an undesirable to a desirable one;
- Altering the stability landscape to make such navigation easier or more difficult; and
- Transformation to become a different kind of system when that is the only viable option left.

In order to understand the resilience characteristics of a water supply system in this study, sensitivity of flow to pressures was used as an indicator variable. High sensitivity of flow to variable pressures indicates low ability to withstand that level of pressure. Similarly, the speed of resumption of flow after a service discontinuation event is an indication of the ability to recover from a disturbance.

As a water supply system consists of ecological, technical and social subsystems as discussed in Section 1.2, the meta-system emphasises different applications of the resilience concept that are inherent characteristics of different subsystems. The water catchment is an ecological subsystem with human interaction. Therefore, it can be interpreted as a socio-ecological subsystem. The treatment plant is primarily an engineering subsystem. The end users can be categorised as belonging to a social subsystem. Considering the water catchment and the treatment plant, the base concepts of socio-ecological and engineering resilience are the key interest in this study. The behaviour and the characteristics of a social system applicable to the end users is complex, and a detailed evaluation of a social system is not within the scope of this research study. The contrasting characteristics of socio-ecological and technical subsystems are illustrated in Table 3.3.

Table 3.3 –Characteristics, focus and context of socio-ecological and engineering resilience (adapted from Folke 2006)

Resilience concept	**Characteristics**	**Focus on**	**Context**
Socio-ecological	Interplay disturbances & reorganization, sustaining & developing	Adaptive capacity, transformability, learning, innovations	Integrated system feedback, cross scale dynamic interactions.
Engineering	Return time, efficiency	Recovery, consistency	Vicinity of a stable equilibrium

Walker *et al.* (2002) referred to socio-ecological resilience as the potential of the system to remain in the same basin of attraction and to maintain its feedbacks and functions. The characteristics of interplay, ability to reorganise, and sustainability are highlighted due to human involvement. Relationships between components within this category are dynamic with considerable scope for complexity across temporal and social scales. Therefore, the emphasis is on adaptability, innovation and learning (Barnes *et al.* 2011)

The treatment plant is a technical or engineering system and engineering resilience refers to the behaviour of a system in the immediate vicinity of a stable equilibrium (Gersonius 2008). The most stable equilibrium is at the lowest elevation in the cup and basin model. This interpretation is concerned with the consistency of the state within the basin of attraction and can be measured by the speed of return to equilibrium following a disturbance. Therefore, the focus is mainly on system recovery, based on the systemic characteristic of return time.

3.5.4 Adaptive capacity and adaptive management

Adaptive capacity is a key systemic property that has a close relationship with resilience. Adaptive capacity was originally defined in biology to describe the capacity to live and reproduce within a specific range of environmental conditions (Gallopin 2006). In general, a species, population, or individual may also better perform by improving its condition within its environment. This is also applicable to human systems which are capable of continuous learning. Hence, adaptive capacity of human systems can be defined as the capacity of any human system to increase (or at least to maintain) the quality of life of its individual members in a given environment or range of environments (Gallopin *et al.* 1989).

In the context of climate change, which is the focus of this study, the Intergovernmental Panel on Climate Change (IPCC) has defined adaptive capacity of a system as *the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*' (IPCC 2007). Smit *et al.* (2000), considering a socio-ecological system referred to the adaptive capacity as the '*ability to make adjustments in ecological-socio-economic systems in response to actual or expected climatic stimuli, their effects or impacts'*.

A system with high adaptive capacity tends to adapt to the situation much faster and reorganise promptly. Considering recovery times of two systems as shown in Figure 3.4, System 2 has better adaptive capacity than System 1 because the recovery time t_{m2} is shorter than $t_{m1.}$ This suggests that system 2 is more resilient than system 1, if system recovery is considered as the only resilience characteristic.

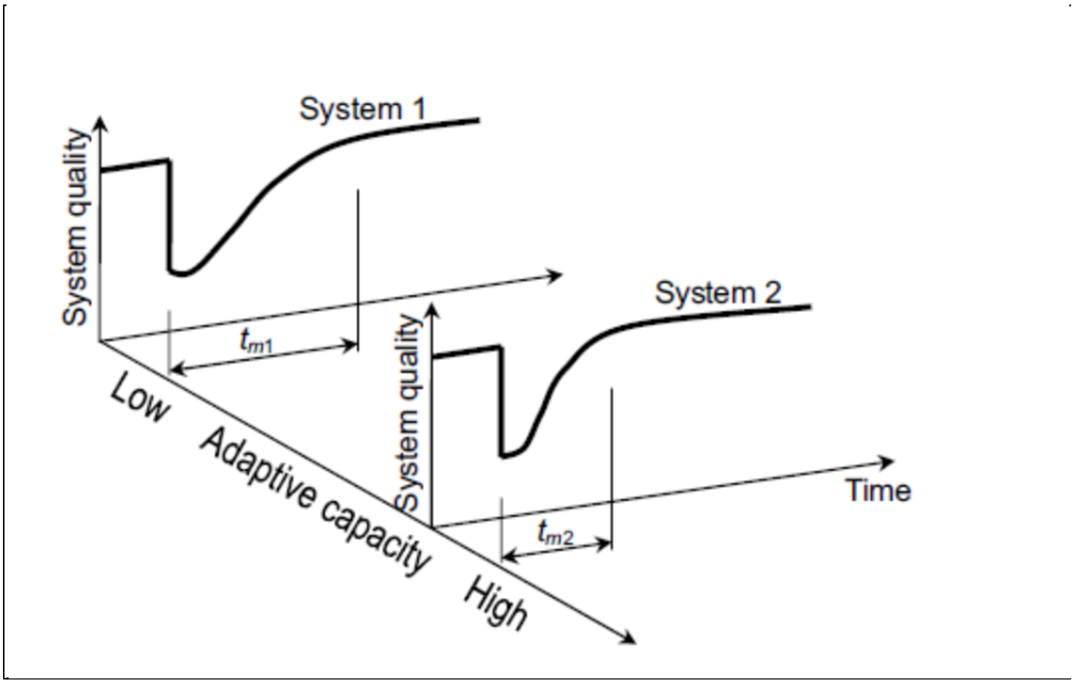


Figure 3.4 – Adaptive capacity of two conceptual systems (adapted from Wang and Blackmore 2009)

Blackmore and Plant (2008) have defined adaptive capacity as the capacity of the actors in the system to influence resilience. From this perspective, adaptive capacity can be identified as the ability of a system to re-configure to continue successful functionality. This is an important element that enhances the resilience of a system.

Formulation of strategies for making use of the adaptive capacity of the system in view of increasing service efficiency is adaptive management. Garmestani and Benson (2013) noted that adaptive management provides the basis for translating resilience theory into practice.

A key component of adaptive management is the 'polycentric system' (Folke *et al.* 2005). Polycentric systems are complex adaptive systems without a central authority controlling the processes and structures of the system (Andersson and Ostrom 2008). Ostrom (2010) noted that polycentric systems are characterised by multiple governance units at multiple scales, with each unit having some capacity to govern at its scale. A water supply system represented by a meta-system at three levels can also be considered as a polycentric system since it encompasses different complex subsystems as multiple governance units. Each unit has some capacity to govern its own operations. Therefore, high adaptive capacity of each subsystem contributes to enhance the overall resilience of the system.

Hence, adaptive capacity is an important characteristic of a dynamic system for its existence. Ability of system elements to change to suit the changing environment will help the system to continue its functionality, enhancing the resilience of the entire system.

3.6 QUANTIFYING RESILIENCE AND SUITABILITY OF THEMATICAL INTERPRETATIONS

Attempts have been made to quantify the resilience of water infrastructure systems using a range of approaches (Kjeldsen and Rosdjerg 2004; Moy *et al.* 1986; Wang and Blackmore 2009; Liu *et al*. 2012). However, Haimes (2009) has pointed out that resilience of a complex system cannot be characterised by a single numerical descriptor. He concluded that system resilience is best understood, and evaluated, in the context of a probabilistic and dynamic set of input threat scenarios, and in terms of a complex set of associated consequences attached to any such threat. Furthermore, the resilience of a system could be measured in terms of a myriad of sub-states that characterise the system for specific time periods and threats. Hence, measuring the system's resilience could be achieved through the unique functionality of that particular system and its responses (outputs) to specific inputs.

A list of relevant empirical models that have been discussed in research literature to define and assess resilience is given in Table 3.4. Although some of these empirical models were not developed in the context of a water supply system, the underlying principles were found to be suitable for adaptation in the current research study. Most of these models are focused on quantifying general resilience and not the specific resilience of the system to a particular type of disturbance. However, the focus of the current research study was to assess the resilience of a water supply system to specifically defined pressures, namely, the consequences of climate change and population growth. Therefore, the parameters should address these pressures and provide adequate information to identify the resilience of the system under these contexts.

Models 1, 2, 3, 4 and 5 in Table 3.4 were developed to assess the resilience of water resource systems. The suitability of these models is discussed below.

Hashimoto et al. (1982) defined resilience as a measure of how fast a system is likely to return to a satisfactory state once the system has entered into an unsatisfactory state. They expressed resilience as a conditional probability, more specifically an average probability of recovery at time step t+1 from a failure state at time step t (Equation 3. 1). Kjeldsen and Rosbjerg (2004) investigated the choice of reliability, resilience and vulnerability estimators for risk assessment of water resources systems. They proposed two equations (Equation 3.2 and 3.3 given below) for quantifying resilience based on two similar definitions given by Hashimoto et al. (1982) and Moy et al. (1986) considering recovery time as a means of quantifying resilience.

$$\text{Resilience} = \mathrm{P}\ \{S(t+1) \in NF \mid S(t) \in F\} \quad \text{...........Equation 3.1}$$

Where S (t) is the state variable under consideration at time t, NF denotes 'Non Failure', F denotes 'Failure', P denotes 'Probability'.

According to this definition, the higher the probability of recovery, higher the resilience. Therefore, in this sense resilience can be expressed as the rapidity of the system returning to satisfactory state after an occurrence of failure.

Table 3.4- Models to quantify resilience

No	Model	Introduced by	Focus	Measured attribute	Comments
1.	Resilience interpreted as a conditional probability R= P $\{S(t+1) \in NF \mid S(t) \in F\}$ S(t) is the state variable under consideration.	Hashimoto *et al.* (1982)	Water resource system	Probability of failure	Probability of failure is a possible indicator to vulnerability of failure.
2.	Time spent in unsatisfactory stage $\boldsymbol{R = \left\{\frac{1}{M}\sum_{j=1}^{M} d(j)\right\}^{-1}}$ d(j) is the duration of the j^{th} failure event and M is the total number of failure events	Kjeldsen and Rosdjerg (2004)	Water resource system	Time spent in unsatisfactory state	Longer time in failure state means less ability to recover.
3.	Maximum consecutive duration the system spends in an unsatisfactory state $R = \{\boldsymbol{max}\{d(j)\}\}^{-1}$ d(j) is the duration of the j^{th} failure event	Moy *et al.* (1986)	Water resource system	Maximum consecutive duration the system spends in unsatisfactory state	Higher consecutive failure duration represents higher frequency of failure and lack of ability to recover.

Table 3.4- Models to quantify resilience

No	Model	Introduced by	Focus	Measured attribute	Comments
4.	Reservoir system performance $m = \frac{(1-\propto)}{\sigma}\mu = \frac{(1-\alpha)}{Cv}$ Where α is the annual yield as a fraction of the mean annual inflow μ, σ is the standard deviation of the annual inflows and Cv is the coefficient of variation of the annual stream flows.	Hazen (1914); Sudler (1957); Hurst (1951)	Water resource system	Annual inflow	By observing the resultant total inflow (water level or storage), it will be useful to establish a relationship with climate variability
5.	Loss of resilience $L = \int_{to}^{t0+tm} [1 - Q(t)]\, dt$ Where Q is the ratio of the system quality to its original (0 means no service available and 1 means neither degradation nor improvement in service), m is the magnitude of an adverse effect occurs at time t_o and t_m is the time taken for restoration.	Wang and Blackmore (2009)	Water resource system	• Degree to which water quality is achieved compared to the pre disruption level • Time to recovery	Degree of recovery with respect to quality and quantity is an important indicator Time to recover also represents ability to recover.

Table 3.4- Models to quantify resilience

No	Model	Introduced by	Focus	Measured attribute	Comments
6.	Networked infrastructure resilience $R= \frac{\int_{t1}^{t2} Q(t)dt}{(t2-t1)}$ $Q(t) =(Q_\infty - Q_0)e^{-bt}$ Q_∞ -capacity of the fully functioning system Q_0 - Post event capacity b - Parameter derived empirically from restoration data following the event. T -time in days post event	Reed *et al*. (2009)	Infrastructure system	Quality difference and time to recovery	As above
7.	Resilience against crossing a performance threshed, $R = \frac{\sum_{i=1}^{N} Yi}{\sum_{i=1}^{N} Di}$ N - number of time intervals in one year Yi - water supplied by the tank Di - demand in the i th interval	Wang and Blackmore (2009)	• Rain water • tank water • supply system	Capacity of a water tank to supply water before crossing a pre defined threshold.	Same principle as above

Kjeldsen and Rosbjerg (2004) further used this concept to quantify resilience by referring resilience to the inverse of the mean value of the time that the system spends in an unsatisfactory state as expressed in Equation 3.2

$$\boldsymbol{R} = \left\{ \frac{\boldsymbol{1}}{\boldsymbol{M}} \sum_{\boldsymbol{j=1}}^{\boldsymbol{M}} \boldsymbol{d(j)} \right\}^{-\boldsymbol{1}} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Equation 3.2}$$

Where d(j) is the duration of the j^{th} failure (higher demand than supply) event and M is the total number of failure events.

Moy *et al*. (1986) defined resilience as the maximum duration that the system spends in an unsatisfactory state. Based on this definition resilience was quantified as given in Equation 3.3.

$$\mathrm{R} = \{\mathbf{max}\{\mathrm{d(j)}\}\}^{-1} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation } 3.3$$

Where d(j) is the duration of the j^{th} failure event as shown in Figure 3.5.

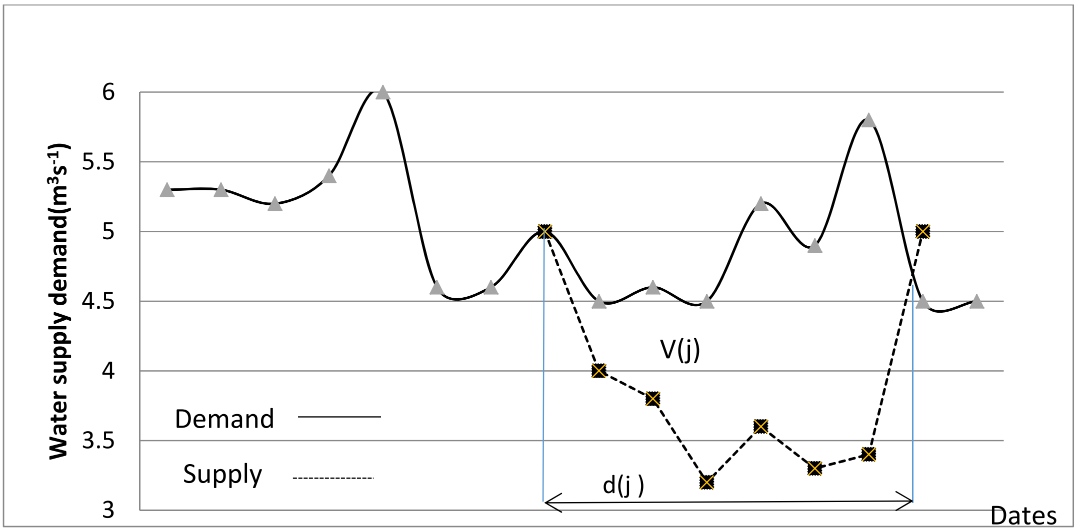


Figure 3.5- Characteristics of duration and deficit volume of a failure event (adapted from Kjeldsen and Rosbjerg 2004)

The Equations 3.2 and 3.3 have been employed to characterise the ability of the system to recover from a disturbance. However, the main variable ‘d(j)’ is governed by demand and supply forces. Hence, in order to quantify resilience based on Equations 3.2 and 3.3, a supply deficit period (demand greater than supply) should be identified. However, in cases where demand is not greater than supply, even for very low supply levels, resilience of the system cannot be assessed using Equation 3.2 and 3.3.

Furthermore, systemic resilience is a concept that highlights characteristics and abilities of the system. Equations 3.2 and 3.3 strive to assess the ability of the system to recover. The selected parameters to measure the ability are the demand and supply. Demand is an external pressure (not a systemic property). Supply indicates the level of performance, which is a systemic property. According to the definition of ‘dj’, lower demand than supply at any point might **not** indicate a deficit period even for a very low supply. In this case, the system might not go into the deficit state merely because of the lower demand compared to the supply and not due to its high resilience.

Another problem of quantifying resilience based on Equation 3.2 and 3.3 is that these do not include factors related to the amount of pressure. Any expression to quantify resilience should include parameters to identify the level of pressure exerted on the system. Therefore, the consideration of failure duration alone (governed by supply and demand) is not adequate to characterise the ***system’s ability*** to recover as further discussed below.

As the intention of Equations 3.2 and 3.3 is to characterise the ability of the system to recover, they should provide results such that high scores represent the ease of recovery. This can be evaluated by considering two systems that are under the same conditions (similar pressure, similar demand) with different levels of recoverability.

Let “O” denote an operational time interval and “F” denote failure time interval, with both having similar number of events.

System 1 – (O O F F F O O O F F F O O O O O O O)

System 2 – (O O F F F O O F O O O F O O O O F O)

The question of which system is more resilient is answered by considering the ability to withstand pressure. System 1 has failed only twice, while system 2 has failed four times. However, system 2 has the ability to recover relatively faster whenever it has failed, indicating higher recoverability. Therefore, each system exhibits different traits. As the two systems show different levels of resilience, it is difficult to determine which system is more resilient under the situation illustrated above.

Applying Equation 3.2 and Equation 3.3 to both systems, Equation 3.2 gives the same result for systems 1 and 2, quantifying resilience as equal to 3, while Equation 3.3 gives the same result for both systems as resilience is equal to 3^{-1}. Therefore, neither Equation 3.2 nor 3.3 can differentiate the level of resilience for different performance levels and the numeric value alone does not provide any useful information about the level of resilience. Hence, as Sirinivasan *et al*. (2009) have noted, Equations 3.2 or Equation 3.3 cannot be considered as satisfactory means of expressing systemic resilience.

Vogel and Bolognese (1995) used the following non-dimensional index (m) given in Equation 3.4 as a representation of resilience of a reservoir system:

$$m = \frac{(1-\propto)}{\sigma}\mu = \frac{(1-\alpha)}{Cv} \text{ ....Equation 3.4}$$

Where α is the annual yield as a fraction of the mean annual inflow μ, σ is the standard deviation of the annual inflows and Cv is the coefficient of variation of the annual stream flows.

Vogel and Bolognese (1995) showed that ‘m’ is related to the probability that a reservoir will recover from failure and argued that ‘m’ is a measure of reservoir system resilience. Accordingly, reservoirs with a ‘m’ value near 0 require more time to recover than reservoirs with a ‘m’ value near unity. Systems with low resilience (m near 0) will have either large values of Cv or large values of α or both. Reservoirs with a value of ‘m’ near or above unity require less time to refill, once empty.

However, this index also considers only the speed of refilling of a reservoir taking into account the annual yield and mean annual inflow. Assessment of one characteristic alone will not be sufficient to determine ‘resilience’ of a complete system as explained above.

Considering the time to satisfactory recovery (in terms of quality), Wang and Blackmore (2009) quantified the loss of resilience (L) of a water resource system as given in the Equation 3.5.

$$L = \int_{to}^{t0+tm} [1 - Q(t)]\, dt \text{ .... Equation 3.5}$$

Where ‘Q’ is the ratio of the system quality to its initial quality (0 means no service is available and 1 means neither degradation nor improvement in service), ‘m’ is the magnitude of an adverse effect occurring at time t_o, and t_m is the time taken for restoration.

The Figure 3.5 below presents a graphical illustration of system resilience for response/recovery in terms of quality.

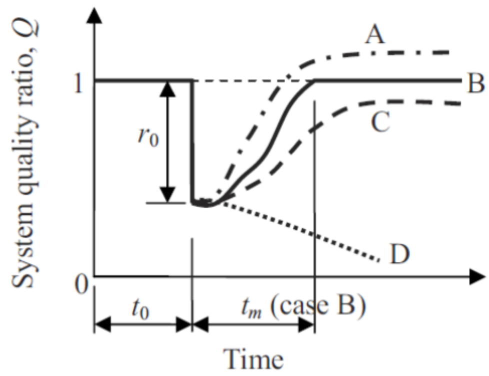


Figure 3.6 – Graphical illustration of system resilience for response/recovery (adapted from Wang and Blackmore 2009)

The two parameters that affect the magnitude of 'L' are the time to satisfactory recovery 't_m', and the residual quality of the system 'Q'. The system may exceed its original state (case A) or suffer some permanent loss as illustrated in case C or D. Under this approach time to recover from an unsatisfactory state as well as the degree of quality after recovery has been taken into account. Therefore, it addresses two attributes of the system for expressing the loss of resilience.

However, a shortcoming of Equation 3.5 is that it does not account for the quantitative aspect of output. For expressing resilience of a water supply system, the quantitative aspect is an essential requirement. It can be explained as follows. Although a system recovers 100% in terms of quality, it may not be able to supply the required quantity of water after a disturbance. That implies failure in terms of supplying an adequate quantity of water. Therefore, quantitative assessment is an essential component of an equation that assesses the resilience of a water supply system. Furthermore, the reason for quality decline is not identifiable in Equation 3.5. The quality decline can be due to reasons such as effects of climate change and/or effects of population growth. Therefore, Equation 3.5 needs to be refined further to identify the reasons for the failure, if it is to be sufficiently reliable to assess resilience to climate change and population growth impacts.

The mathematical equations to quantify resilience discussed above offer a very good foundation to think of how to assess resilience in terms of numerical terms. Apart from the advantages and shortcomings of the equations discussed above, one of the common shortcomings, is that most of them are focused on assessing one characteristic and use one parameter for quantifying resilience. For a complete water supply system it is difficult to assess the resilience of the system considering only one parameter. It needs a range of parameters to assess system characteristics to identify the behaviour of the water supply system which determines systemic resilience. The advantage of studying these equations is that the parameters used in these equations can be used for developing suitable indicators to assess resilience characteristics of a water supply system. Based on the knowledge gained from the review of research literature, the applicability of the resilience concept specifically to a water supply system is discussed in the following sections.

3.7 CONTRIBUTING FACTORS FOR ENHANCING SYSTEMIC RESILIENCE OF A WATER SUPPLY SYSTEM

For a complex system, Chang and Shinozuka (2004) noted the following factors that enhance the resilience of a system:

- ***Robustness:*** The strength or ability of the system to withstand a given level of stress or demand without suffering unacceptable degradation or loss of function.
- ***Redundancy:*** The availability of elements or system that is substitutable and can be activated when disruptions due to disturbances occur.
- ***Resourcefulness:*** The capacity to identify problems, establish priorities and mobilise resources in the event of disruptions. It can be further conceptualised as consisting of the ability to apply material and human resources to meet established priorities.
- ***Rapidity:*** The capacity to meet priorities and achieve goals in a timely manner.

It is important to identify in a water supply system, the attributes that facilitate the above-mentioned resilience factors. From the knowledge gained from the review of research literature, the following were identified as contributing to strengthen the above properties and are able to further explain how they contribute to enhancing systemic resilience:

- Climate elasticity of streamflow (explained in detail in Section 2.3.5) of the catchment;
- Available storage;
- Capacity to treat low quality water;
- Connectivity to multiple treatment plants;
- Alternative supply sources ;
- System management procedures.

Climate elasticity of streamflow of the catchment

Water availability in the system is determined by inflow and storage. Storage is related to rainfall as follows:

Rainfall $\xrightarrow[+]{}$ runoff $\xrightarrow[+]{}$ streamflow $\xrightarrow[+]{}$ **storage**

The above processes are positively related as indicated by the '+' sign next to the arrow head. This means that when rainfall increases or decreases, inflow and storage also increases or decreases. Therefore, based on the above relationship, storage tends to reduce with the reduction in rainfall. However, in a resilient system, the supply level may not drop below the critical threshold even under the majority of low rainfall conditions. The degree of proportional decrease of streamflow due to climate change (change of rainfall parameters) depends on climate elasticity of streamflow in the catchment as discussed in detail in Chapter 2.3.5. Catchments with low streamflow elasticity (low proportional change in stream flow to climate change) show higher resilience due to high robustness.

Available storage

The strength of the system to withstand pressure (robustness) can also be expressed in terms of the maximum duration in which the system is capable of maintaining its highest potential supply level under pressure. Larger available storage (buffer capacity) increases the duration that the system is able to maintain the required supply level under the pressure of low rainfall conditions, thus enhancing the resilience of the system.

Capacity to treat low quality water and connectivity to multiple treatment plants

The treatment plant acts as an internal element that restores the degraded water quality in the system. Under extreme water quality deterioration events due to climate change, the rate of purification can reduce. This will reduce the final output from the system, thus increasing the failure probability. However, if the treatment plant is capable of treating even low quality water resulting from climate change, the system shows high robustness.

Connectivity to multiple treatment plants allows more options to obtain treated water without depending on only one treatment plant. It is an example of *redundancy* as well as *resourcefulness* as explained above at the beginning of Section 3.7.

Alternative supply sources

As discussed, climate change tends to reduce the volume of water stored. However, if alternative *redundant* supply sources (which will be activated in a crisis) are available, *robustness* of the system is high. As illustrated in Figure 3.7, activation and deactivation of an alternative supply source creates a negative relationship that operates as a balancing mechanism.

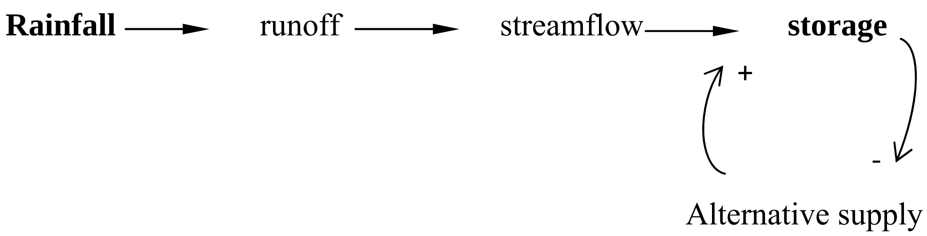


Figure 3.7 – Effect of an alternative supply

When the storage volume becomes low, the alternative sources are activated to increase storage. This process compensates for low inflow due to potential climate change impacts, thereby enhancing the resilience of the system.

System management procedures

A system equipped with an efficient management strategy has the capacity to meet service standards across a variety of anticipated scenarios. This is very important in a crisis situation. It ensures the activation of the attribute, *rapidity* (defined at the beginning of this Section 3.7) of the system. However, this involves human interactions. Therefore, it is not an automatic response by the system itself.

3.8 MANAGEMENT STRATEGIES BASED ON RESILIENCE APPROACH

Contingency and crisis management are crucial aspects in essential infrastructure management. In an effective crisis management strategy, preparedness for disasters due to 'non-routing' of adverse events is an essential requirement. Non-routing events are the incidences that might happen outside the regular cyclic processes. Barnes *et al*. (2010) pointed out that the following managerial guidelines could form an effective institutional and organisational response to non-routing events:

- ***Prevention:*** ensuring infrastructure is built to regulated standards and managed effectively both as stand-alone domains and as connected domains.
- ***Preparation:*** planning for the known and possible instances of failure, disturbance and variability within either of the domain layers.
- ***Response:*** recognising emergent crises and ensuring timely responses, some of which are likely to differ in different domains.
- ***Recovery:*** restoring normal function and applying adaptive strategies in all domains, as needed.

The performance of a system varies under adverse conditions. Ouyang and Osorio (2011) noted three stages of performance variations in response to adverse conditions. These are the disaster prevention stage, damage propagation stage and recovery stage. These three stages are illustrated in Figure 3.8.

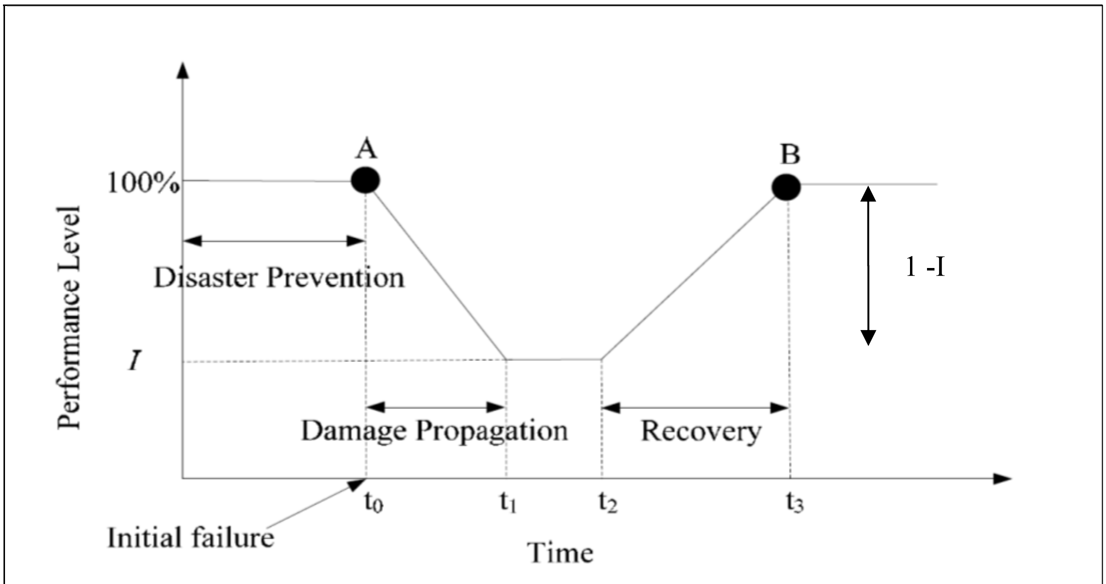


Figure 3.8 - System performance-response curve (adapted from Ouyang and Osorio 2011)

Prevention, preparation, response or recovery actions should be taken at the most appropriate stage of the performance-response curve to achieve efficient service provision. System performance curve and the relevance of the type of action at the appropriate stage are explained below with reference to Figure 3.8.

Under normal operations, the system performance level is at 100%. However, when the initial failure occurs at point A (Figure. 3.8), the damage propagates and the performance level drops to a certain value I, where 1-I was defined as the maximum impact level. After a period of recovery time, the system reaches a new steady state performance level at point B, which may be better or worse than its original state.

The disaster prevention stage mainly reflects the system’s resistant capacity. It is the ability of the system to prevent the initial failure. Prevention strategies at this stage enhance resilience by strengthening initial resistant capacity. Increasing storage and treatment capacities with a view to preventing future supply shortages is an example for such prevention strategies.

The damage propagation stage mainly reflects the absorptive capacity. It is the degree to which the system can absorb the impact of initial failure. High absorptive capacity results in a low rate of damage propagation. In Figure 3.8, the value (1-I), measures the absorptive capacity. Ouyang and Osorio (2011) defined this as a resilience index. At the initial stage of damage propagation, preparation strategies are useful to prevent further damage. A common approach by water supply authorities is the introduction of water restrictions for maintaining storage levels for a longer period as a precaution in the event of a predicted drought. As the damage propagates further, strategies such as prompt responsive actions through continuous monitoring are more appropriate at this stage

The third (recovery) stage mainly reflects the restorative capacity. It is the ability of the system to be repaired quickly and effectively. Recovery strategies through effective management intervention are more appropriate at this stage.

The knowledge of systemic resilience enables the consideration of different management strategies at different times and stages of performance. Taking appropriate action at the correct time leads to the enhancement of the effectiveness of the management strategy. Table 3.5 highlights possible resilience improvement actions for a water supply system that could be taken at different stages of performance variations with reference to Figure 3.8.

Table 3.5- Resilience improvement actions at different states of a water supply system (partially adapted from Ouyang and Osorio 2011)

Stage	**Management strategy**	**Resilience improvement actions**
First stage	Prevention, Preparation	• Identify failure causing pressure magnitudes • Strengthen key components • Monitor pressure levels and system states • Improve decision support platform • Introduce precautionary measures (eg. water restrictions)
Second stage	Response	• Introduce demand management strategies • Continuous monitoring • Use redundant resources
Third stage	Recovery	• Improve situational awareness and decision support platform • Establish efficient communication channels and coordination

Knowledge of systemic resilience to pressures with high uncertainty is more useful than that of pressures with smooth and gradual variations because for the latter case, these pressures are reasonably predictable and thus the system can be designed or modified to operate within the predicted boundaries. When the uncertainty of pressures is high, it is difficult to design the system for a wide operational range. In such cases, the knowledge of systemic resilience helps to bridge the gap between the operational capacity of the system and the designed limits of the system by taking appropriate precautionary measures prior to a crisis situation. Constant monitoring, adjusting, engaging in long term planning and being open to transition to a desirable alternative regime are essential for maintaining resilient systems (Wang and Blackmore 2009).

3.9 INDICATORS TO EVALUATE RESILIENCE

As a means of evaluating systemic resilience of a water supply system, a suitable set of indicators are required. Use of indicators is a widely accepted method in scientific analysis in many different fields and a thorough understanding of the limitations of indicators is critical for their proper selection and use. In this regard, an extensive analysis of indicators and indicator selection was undertaken.

Different interpretations can be found in the literature describing the fundamental characteristics and purposes of indicators. Some of the most relevant interpretations are given below:

- *An indicator is a pointer. It can be a measurement, a number, a fact, an opinion or a perception that points at a specific condition or situation, and measures changes in that condition or situation over time. In other words, indicators provide a close look at the results of initiatives and actions (CIDA 1997).*
- *Indicators are succinct measures that aim to describe as much about a system as possible in as few points as possible. Indicators help us understand, compare it and improve it (NHS 2012).*
- *An indicator provides a sign or a signal that something exists or is true. It is used to show the presence or state of a situation or condition. In the context of monitoring and evaluation an indicator is a quantitative metric that provides information to monitor performance, measure achievement and determine accountability (UNAIDS 2010).*

An understanding of the limitations of indicators guides the proper direction of the decision making process. It is important to understand that indicators only indicate about a particular status by providing information that must be understood in its context. Indicators mainly rely on numbers and numerical techniques (NHS 2012). Therefore, further actions based on the information obtained from indicators are the responsibility of relevant decision makers.

From the above interpretations, an indicator can be understood as a tool that provides information about a measure that cannot be defined directly. The information provides the background for analysing a problem logically and enhances the proper decision making process. Hence, the primary objective of indicator usage can be identified as obtaining information for further appropriate actions. For assessing resilience of a system, information about system behavior and the pressures applying on the system are required. An indicator can be used to obtain and evaluate the necessary information for assessing the resilience of a system. However, there are different types of indicators. The following section discusses the types of indicators in view of understanding suitable indicators for assessing resilience of a water supply system.

3.10 TYPES OF INDICATORS

3.10.1 Global, National and Project indicators

UNAIDS (2010) categorised indicators into three different levels. They are; global level, national level and project level, as depicted in the pyramid given in Figure 3.9. The indicator pyramid illustrates the dependability of each level of indicator on the other.

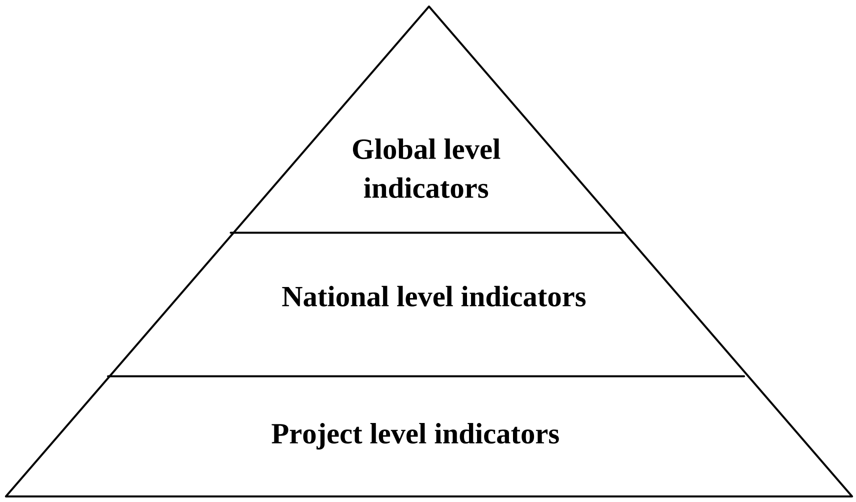


Figure 3.9 – Indicator pyramid (adapted from UNAIDS 2010)

The first level of indicators is at the project level (UNAIDS 2010). Higher levels of indicators are generally based on this first level of indicators. The project level indicators are used within a limited context. For example, a set of performance indicators that evaluate specific types of services can be categorised as project level indicators, which can be used to rank similar organisations according to their performance efficiency. National level indicators aggregate data from the project level to provide an overview of a country’s response. The aggregation of data from national level indicators in multiple countries provides data for global level indicators.

3.10.2 Quantitative and Qualitative indicators

Quantitative indicators express conditions or performance information in numerical terms such as whole numbers, fractions, ratios and percentages. Qualitative indicators express a relative judgment. CIDA (1997) highlighted a more precise distinction between quantitative and qualitative indicators by defining quantitative indicators as a measure of quantity and qualitative indicators as people's judgments and perceptions about a subject, such as the confidence those people have.

The two types of indicators (qualitative and quantitative) are in fact complementary and both are important for effective monitoring and evaluation (Pereira 2011). Bastia (2000) argued that qualitative analysis is important to obtain an in-depth understanding of the changes that take place in any social setting. Hayati *et al.* (2006) pointed out that despite the complexity of using both approaches, qualitative indicators increase the accuracy and transparency of the quantitative indicator data.

There can be a considerable overlap between qualitative and quantitative indicators making it difficult to distinguish one from the other. Two ways of distinguishing between these two are by their sources of information and the way in which the information is interpreted and used (CIDA 1997). For example, information on the same issue can be interpreted in terms of percentage (using a quantitative indicator) or may be interpreted as an opinion: high, moderate or low (using a qualitative indicator). A set consisting of qualitative and quantitative indicators will evaluate a problem more effectively.

3.10.3 Performance evaluating indicators

A common use of indicators is for performance evaluation leading to the development of a specific set of indicators across a range of areas. Performance evaluating indicators can be further subdivided according to the measure of performance as indicated by WHO (2013) and Australian Government Performance Indicator Resource Catalogue (2006). The subdivisions of performance evaluating indicators are given in Table 3.6.

Table 3.6- Types of performance evaluating indicators (adapted from WHO 2013 and Australian Government Performance Indicator Resource Catalogue (2006)

Type of indicator	Interpretation
Input indicators	Resources needed for the implementation of an activity or intervention
Process indicators	Measure whether planned activities took place
Performance indicators	Metrics or factors that tend to indicate the health, progress and /or success of a project, process or area of service delivery
Output indicators	Output indicators add more details in relation to the product (output) of the activity
Outcome indicators	Outcome indicators refer more specifically to the objectives of an intervention than its 'results'
Impact indicators	Provide information about the consequences of a process or activity

The understanding of the indicator categories as explained above leads to the formulation of clear characteristic requirements for suitable indicators for this study. It is clear that the required indicators are at the project level. This study is only focused on 'systemic' resilience of a water supply system where there is no involvement of national or global scale data.

3.11 USES OF INDICATIORS

3.11.1 Indicators in different disciplines

Selection and use of indicators are unique to the nature of the assessment. For example, at the initial stage of water infrastructure development, it is required to identify what percentage of people has access to water sources. That is key information for developing further water resources for that community. Climate change and environmental sectors need different information and indicators are selected accordingly. Indicators used in different areas as listed by the World Bank (2013) are given in Table 3.7. When selecting resilience indicators in this study, similar parameters were considered for quantifying the required information.

Table 3.7 – Simple indicators of different fields (Data source World Bank 2013)

Indicators of different sectors	Expressed in terms of
Infrastructure	
Improved water sources (rural)	% of rural population with access
Improved water sources (urban)	% of urban population with access
Renewable internal freshwater sources per capita	Cubic meters
Annual fresh water withdrawal (domestic)	% of total fresh water withdrawal
Climate Change	
CO_2 emissions	metric tons per capita
Nitrous oxide emissions	thousand metric tons of CO_2 equivalent
Other greenhouse gas emissions, HFC, PFC and SF6	thousand metric tons of CO_2 equivalent
Environment	
Organic water pollutant (BOD) emissions	kg per day
Water pollution, chemical industry	% of total BOD emissions
Forest area	% of land area
Financial Sector	
Bank capital to assets ratio	%
Bank non-performing loans to total gross loans	%
Deposit interest rate	%

3.11.2 Indicators for problem evaluation

Winograd *et al.* (1999) used indicators for evaluating common problems of low water availability and low water quality. The Pressure-State-Impact-Response approach (Figure 3.10) adopted by Winograd *et al*. (1999) illustrates the use of indicators for understanding the problem by evaluating the problem at different stages.

Figure 3.10 illustrates how two common problems in water supply, low water availability and low water quality, can be explored by analysing the problem in four stages in which different issues contribute to the main problem. The issues in the four stages can be better understood by analysing them separately.

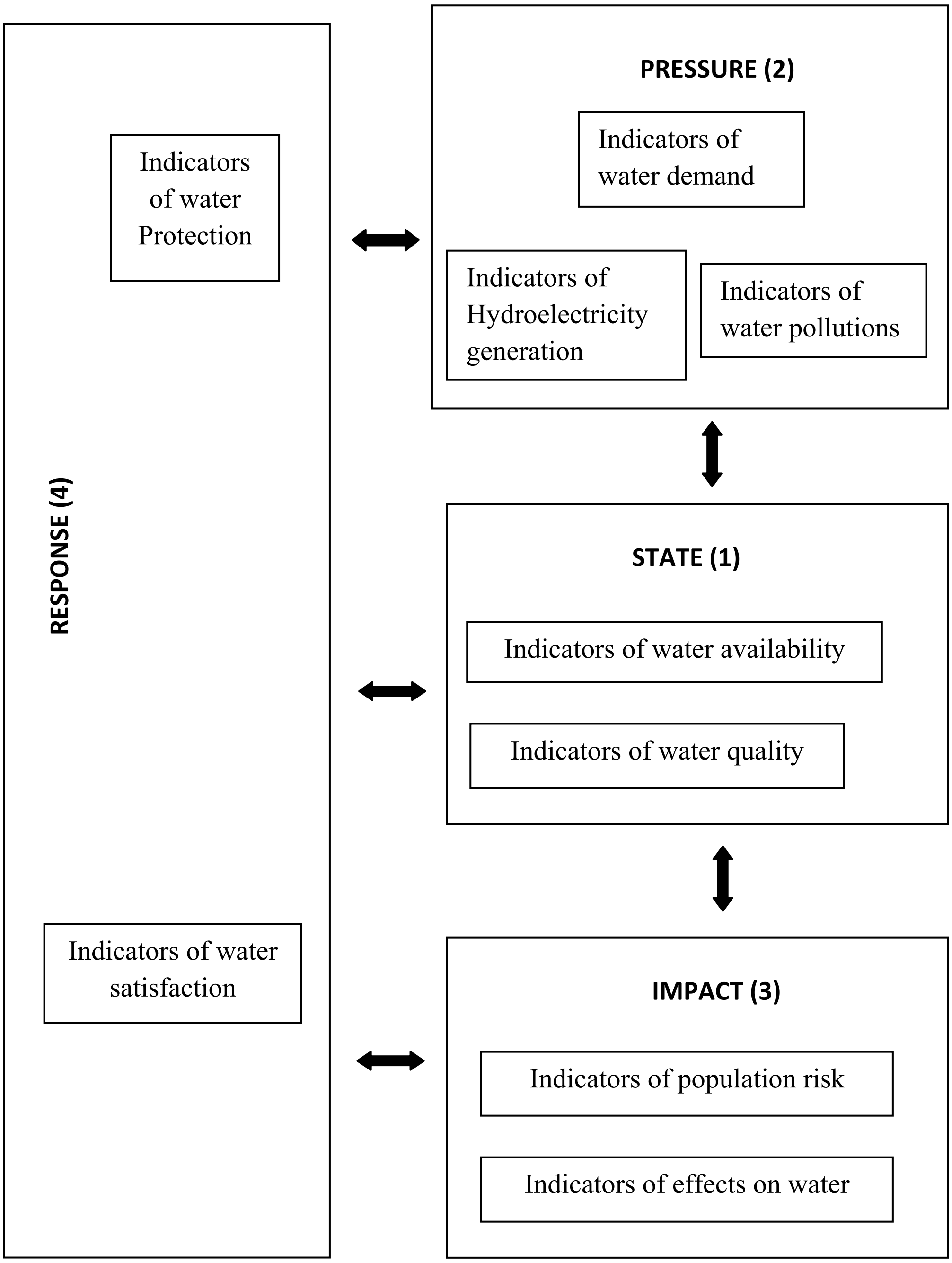


Figure 3.10 – Usage of indicators at different stages (adapted from Winograd *et al.* 1999)

As noted by Winograd et al. (1999), the problem of water availability and water quality is analysed in four separate stages. The state variable (stage 1 in Figure 3.10) describes the problem using the indicators of water quality and availability. The pressure variable describes the underlying causes of the problem. For example, higher water demand for domestic use and electricity generation can cause water quality and quantity issues. The impact variable indicates the consequences of the problem. The response variable includes the actions required for preventing further damage, such as policies and investments that can be introduced to mitigate the problem.

Selecting indicators according to the Pressure-State-Impact-Response approach represents a clearly structured way of presenting indicators, compared with a project-based approach. The approach to be adopted is as follows:

- indicators of demand, hydropower generation, and pollution are categorised as pressure indicators;
- indicators of availability and quality are categorised as state indicators;
- indicators of effects and risk are categorised as impact indicators; and
- indicators of protection and satisfaction are categorised as response indicators.

Structured in this way, the indicators in each category can also be aggregated into four indices as shown in Table 3.8.

Table 3.8 – Aggregation of indicators of different problem stages to form broader indices (adapted from Winograd *et al.* 1999)

Problem stages		Indicators of each subsector	Aggregated information
PRESSURE	Indicators of Demand	Total demand (m^3) Use efficiency (%) Recycling potential (%)	Water vulnerability index
	Indicators of power Generation	Number of dams (No) Kilowatts per hectare inundated (kW) Hydroelectricity production (mW)	
	Indicators of Pollution	N emission into water body(kg) Other emissions (kg)	
STATE	Indicators of availability	Reserves (m^3) Rate of recharge (m^3/yr) Annual rainfall (mm) Annual extraction as % of total (%)	Water quality index
	Indicators of quality	Biochemical oxygen demand (mg/L) Chemical oxygen demand (mg/L) Eutrophication Acidification	
IMPACT	Indicators of effects	People affected by diarrheic diseases (No.) Population affected by inundation (No.) Toxicity/ heavy metal concentration	Climatic risk index
	Indicators of uncertainty	Population risking inundations (No.) Capital risking inundation (No.)	
RESPONSE	Indicators of protection	Watershed land use Watershed protected area	Safe water index
	Indicators of satisfaction	Access to potable water (%) Access to drains (%) Aqueducts (No) Treatment of used waters (%) Water price (\$/ m^3)	

This quantification of information as shown enables the decision makers to understand the actual positive or negative aspects of the problem. In other words, indicators provide a transparent diagnostic checklist guide as noted by Kothari *et al.* (2011). Accordingly, appropriate decisions can be made.

As shown above, the information to analyse the problem has been obtained by separating the main problem into different segments. For assessing resilience of the system, information regarding the pressure and corresponding output (system behavior variations) should be obtained and evaluated. Indicators can be used to obtain such information. However, the required information should be clearly identified and the development of the indicators should be focused on obtaining that information.

3.12 SUMMARY

The broad nature of the resilience concept creates difficulty in understanding the concept. However, systemic resilience can be interpreted as the capacity a system has, and what it does to anticipate and adjust to changes, to absorb impacts and disturbance in order to retain its structure and function. The operational features of the resilience concept can be used as an effective management tool. However, the method of operationalising resilience characteristics depends on the type of infrastructure system.

Different approaches have been introduced to make use of the operational features of the concept. Resilience characteristics in relation to socio-ecological and technical context were the main focuses of this study, as a water supply system lies within socio-ecological and technical subsystems. Features of a water supply system that contributes to enhancing resilience were identified.

Numerous mathematical expressions for assessing infrastructure resilience have been used by past researchers. However, when considering a complete water supply system, the parameters and the equations used in past research studies to measure resilience have significant limitations. Therefore, a scientific method for systematically assessing resilience of a water supply system will be critical for defining current and future management needs and policy decisions. This needs an in-depth understanding of the concept of resilience and the interrelated process of a water supply system. The knowledge of systemic resilience facilitates implementation of the most appropriate strategy at the relevant stage of output variation in order to avoid service failure.

As the resilience of a system can be interpreted related to the ability of the system to perform under pressure, a suitable set of performance indicators can be used as a means of evaluating systemic resilience. Since a standard set of indicators has not been introduced to evaluate the resilience of a system, a preliminary investigation was carried out through the literature review about the types of indicators and how indicators can be used to identify system properties and for problem solving.

Chapter 4: Research Design and Methods

4.1 BACKGROUND

The research design for this study needed to include the development of an approach for linking resilience characteristics of a water supply system to a suitable resilience assessment method, and the application of the approach to an existing water supply system as a case study. The pressures on a water supply system considered in this study were climate change and population growth and Chapters 2 and 3 discussed the impacts of climate change and population growth on water supply systems along with the fundamentals of indicator selection for resilience assessment which is essential for the development of the research methodology.

From Chapters 2 and 3, it was identified that the discussion of following items forms a basis for development of the research methodology;

- Summary of key elements of system resilience assessment (from Chapters 2 and 3);
- System modelling and simulation;
- Selection of indicators for evaluation;
- Evaluation of modelled system outputs.

This chapter discusses the research methodology adopted to develop the research framework for studying resilience of water supply systems and also discusses the study approach used. The case study area is discussed in Chapter 5 and the method required for the development of a simple simulation model of a water supply system is discussed in Chapter 6. As an evaluation technique, use of indicators was proposed and the indicator development procedure is discussed in Chapter 7. The system behaviour under different scenarios simulated by the developed model is discussed in Chapter 8 and the behavior is analysed in Chapter 9 using the selected indicators.

4.2 RESEARCH METHODOLOGY

4.2.1 Summary of key elements of resilience assessment

Chapters 2 and 3 provided a critical review of literature as the initial step to develop a conceptual framework to link resilience characteristics of a water supply system to a suitable method for resilience assessment. It was identified that two key types of disturbance/pressure were acting on a water supply system relevant to this study. These were climate change and population growth. It was identified that these two factors formed the basis for the selection of suitable indicators for assessing resilience characteristics of the system..

Chapter 2 focused on climate change and population growth on water supply system functionality. This revealed that climate change can significantly influence the quantity of water inflow to a storage reservoir. Degradation of physical and chemical water quality parameters were identified as another consequence of climate change. Population growth, resulting in increased demand, can result in possible decrease in service delivery by the system, while urban expansion into the water supply catchment due to population growth can also lead to a deterioration of water quality.

Chapter 3 reviewed the definitions and key concepts of resilience and the relevant research studies that have focused on assessing the resilience of different systems. Types of indicators and how the indicators can be used for identifying different aspects of a problem were also discussed as a basis for identifying a set of suitable indicators for this study. The proposed indicators for this study fell into the quantitative indicator category. This is due to the primary dependency of systemic resilience on output in terms of treated water volume. Water quality variations in output were not assessed separately. The qualitative variations were allowed to be reflected as quantitative changes in output volume by reducing the production rate of output. The reduced rate of output production accounts for water quality deterioration because the rate of treatment reduces for low quality water. Therefore, the information required from the indicators was about the variation in the quantity of output flow rather than the variation in quality.

Focusing on indicators, other than being at a project level, the intended indicators included mixed characteristics of performance indicators, output indicators as well as impact indicators. This was due to the fact that the indicators relevant to this study needed to reveal information about system output –identified as the key indicator of system performance. Hence, the required indicators can be categorised as project-level, quantitative and performance evaluation indicators.

In order to develop a framework for evaluating the resilience of a water supply system, the following aspects were required to be identified by the knowledge gained through the literature review.

- Operational resilience characteristics of a water supply system;
- Methods for assessing resilience;
- Failure criteria of a water supply system;
- Relationship between resilience and the surrogate measure.

Based on the literature, each of the above were identified and discussed below.

Operational resilience characteristics of a water supply system

The 'ability to withstand pressure' and 'ability to recover' were identified as the key operational resilience characteristics to be evaluated in this study. The 'ability' of the system was assessed in relation to performance (output) variations. In order to assess performance variations, the dynamic process of output production had to be identified. Accordingly, 'water flow' was considered as the dynamic process of a water supply system and the potential 'supply volume' of potable quality water was taken as the physical measure of performance.

Failure criterion of the water supply system

The failure state of the system was defined as the failure to supply at least 50% of the demand at any given time. It was assumed that regulations such as water restrictions can reduce typical demand and avoid the system shifting to failure state.

Methods for assessing resilience

As the literature has emphasised, resilience may not always be directly measurable. Consequently appropriate "*surrogate*" indicators may be required for resilience assessment in order to determine systemic resilience. However, there is no single 'correct mechanism' for developing resilience surrogates (Carpenter *et al.* 2005). As a method of evaluating resilience characteristics of a water supply system, a set of suitable indicators were intended to be used. A detailed discussion about the selection of indicators is provided in Chapter 5. Furthermore, systemic resilience in terms of a system's 'ability' to maintain functionality to provide successful services under pressure can be assessed by the likelihood (probability) of failure. Accordingly, *probability of failure* was considered as the *surrogate measure* of resilience of a water supply system.

Relationship between resilience and the surrogate measure

Due to the diverse and abstract nature of the resilience concept, a mathematical equation between failure probability and resilience is difficult to be derived. Therefore, resilience was conceptualized as being inversely proportional to failure probability. The relationship between the surrogate measure (probability of failure) and the pressures was developed based on the following expression.

$$Resilience \rightarrow \frac{1}{Probability\ of\ failure}$$

Probability of failure depends on adverse pressure acting on the system and the limit of the failure threshold. The failure threshold as defined in this study is related to the demand. Hence, a system with higher demand tends to reach the failure threshold quicker than that of lower demand, resulting in high probability of failure. Hence the probability of failure, the adverse pressure and failure threshold can be related as follows

$$\text{Probability of failure} \xrightarrow{\textit{Depends on}} \text{(adverse pressure, failure threshold)}$$

Accordingly, the approach illustrated in Figure 4.1 was adopted for assessing the resilience of a water supply system.

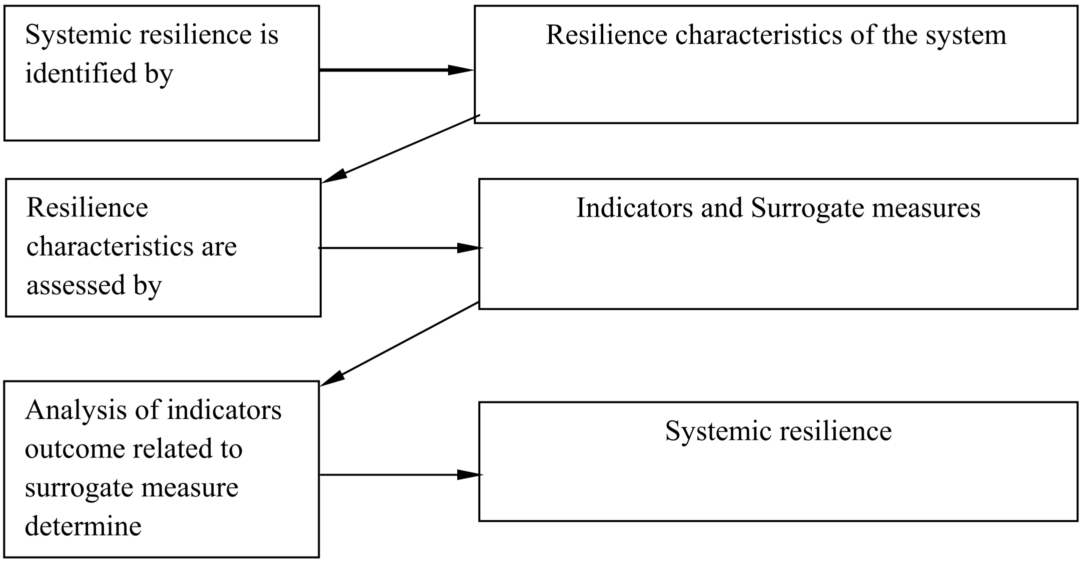


Figure 4.1-Schematic diagram showing the approach for resilience assessment

Based on the above relationships the probability of failure was considered as a dependent variable of pressures created by demand and the low rainfall conditions. The variations of probability of failure was illustrated in a three dimensional space in order to identify the early action trigger points which is demonstrated in Chapter 9.

4.2.2 System modelling and simulation

Modelling an existing system was the method adopted to analyse the system behaviour in order to obtain the probability of failure under different pressure scenarios. The key areas required to be focused for selecting an existing system and modelling the system are discussed below:

- Criteria for selecting a water supply system;
- The characteristics of the selected system;
- Model development.

Criteria for selecting an appropriate water supply system

When selecting a water supply system as the case study, the following considerations were taken into account:

- A complex system with multiple storages and treatment plant facilities where the application of the resilience concept could be rigorously evaluated;
- A system with a large service area where population growth would be significant;

- A system with surface water supply sources which are likely to experience climate change and population growth impacts;
- Easy access to data and information sources relating to the system.

The characteristics of the selected system

Considering the above criteria, the South East Queensland water supply system- SEQ Water Grid- was selected for modelling as the case study. It is one of the largest water supply systems in Australia, operating at a regional basis and having multiple storage reservoirs and treatment plants. The main reason for selecting the SEQ Water Grid as the case study was to emphasise the usefulness of applying resilience as a management concept for a complex system. Further details about the SEQ Water Grid and the service are given in Chapter 5 of the thesis.

Model development

The development of the SEQ Water Grid model required key considerations. These included the conceptualisation of the water supply system, selection of the simulation period and the selection of a suitable modelling technique. Accordingly, the water supply system was conceptualised as a meta-system as discussed in Chapter 1. The simulation period was selected as five years and a mechanism to input 'average' rainfall data was introduced. As the variations in the output in accordance with input variations required to be investigated, a system dynamics modelling technique was selected as the most suitable for this study. The modeling procedure is explained in Chapter 6.

4.2.3 Selection of indicators

The simulated results needed to be evaluated for assessing the resilience characteristics of the system. For evaluation, a suitable set of indicators were intended to be used. However, as a standard suite of indicators was not available for evaluating resilience characteristics, a careful analysis of system behavior was required for identifying the parameters for developing indicators. The procedure for identifying a suite of indicators is discussed in detail in Chapter 7.

4.2.4 Evaluation of modelled system output

The evaluation was based on following aspects in order to explore the resilience characteristics of the system.

- Evaluation of the system's ability to withstand pressure and ability to recover;
- Evaluation of variations of the above 'abilities' of the system under predicted climate change and population growth impacts in the future.

Evaluation of system's ability to withstand pressure and ability to recover

A system's resilience (ability to withstand pressure and to recover) could be assessed by evaluating the variation in output in relation to the failure state thresholds. The method adopted to evaluate the system output in this study was model simulations under the pressures of decreasing rainfall and increasing demand. The changing state of the system was selected for evaluation against the defined failure threshold (given in Section 4.2.1). Higher probability of failure under the applied pressure indicates low ability to withstand that specific level of pressure. Similarly, the ability to recover was evaluated in terms of the time to recover. For determining the magnitude of pressure that the system can absorb before reaching the threshold pressure and triggering a failure state, the proposed indicators were used.

Evaluation of the system's ability to withstand predicted pressures

In order to account for future demand, apart from pressure of low rainfall, demand increase was included for evaluation. In this context, three independent variables were considered in the analysis. These were rainfall, storage and demand. A Logistic Regression model was developed for predicting the combined effects of all three variables simultaneously.

4.3 STUDY TOOLS

4.3.1 System dynamics model

System dynamics modelling was selected as a primary analytical tool of this research study, as this type of modelling approach is commonly used for decision making in water management planning. System dynamics can create models that can be readily used to understand the relationships between a system's behaviour over time and its structure (Wolstenholme 1990). Integrated system models have been used to measure the performance of policy alternatives in relation to a set of objectives and performance measures established by water managers and stakeholders (Lopez-Calva et al. 2001).

System dynamics software such as STELLA, Madonna, GoldSim, Simulink, iThink, Vensim, and Powersim are based on the standard stock-and-flow approach developed in the late 1950s and early 1960s. Models based on system dynamics are built using three principal elements, namely, stocks, flows, and converters, and focus emphasis on understanding the feedback structure of systems. System dynamics software packages are typically used for simulating engineering and scientific systems. Different software packages have specific strengths and limitations. Features of most common dynamic software packages are given in Table 4.1, which formed the basis for identifying the most suitable software for this study.

Table 4.1 – Features of commonly used system dynamic software packages (adapted from Rizzo et al.2005)

Software package	Data input format	Operating system	Integration method	Sensitivity analysis
STELLA V 8.1	Excel, Text	Windows/Macintosh (Graphical interface)	Eular, Runge-Kutta	Built-in
Berkeley Madonna V 8.0	Excel, Text	Windows (Graphical interface)	Eular, Runge-Kutta, Rosenbrock, Manual	Built-in
GoldSim Pro V 9	Excel, Text	Windows (Graphical interface)	Eular	Manual
Simulink V 6.1	Excel, Text	Windows/Macintosh (Graphical interface)	Eular, Gear,Runge-Kutta, Rosenbrock, Manual	Manual

Table 4.1 shows that the four software packages compared have similar features that are suitable for the study. However, out of the four packages, STELLA, developed by Isee System, inc., is the most user friendly software. Therefore, for modelling the SEQ Water Grid, STELLA was selected as the modelling platform. It has high performance and fast simulation capability. In addition, it includes the following key features that provide a flexible programming environment:

Mapping and Modelling

- Intuitive icon-based graphical interface that simplifies model building;
- Stock-and-Flow diagrams that support the common language of system thinking and provide insight into how systems work;
- Causal Loop Diagrams that present overall causal relationships;
- Automatically generated model equations;
- In-built functions that facilitate mathematical, statistical and logical operations;

- Multi-dimensional arrays that simply represent repeat model structure.

Simulation and Analysis

- Sensitivity analysis that reveals key leverage points and optimal conditions;
- Partial model simulations that focus analysis on specific sectors or modules of the problem;
- Presentation of results as graphs, tables, animations and files;
- Dynamic data import/export links to Microsoft Excel or CSV files.

Communication

- Input devices including knobs, sliders, switches and buttons;
- Multimedia support for graphics, movie sounds and text messages;
- Model security feature that facilitates locking or password protection.

As STELLA had all the required features for modelling the SEQ Water Grid for simulation under different pressure scenarios, it was selected as the modelling software in this study.

4.3.2 Logistic regression

Regression is a way of observing and understanding relationships between dependant and independent variables. These relationships can be used for predictions. Logistic regression measures the relationship between a categorical dependent variable and usually (but not necessarily) one or more independent variables, by converting the dependent variable to probability scores.

Logistic regression can be binomial or multinomial. Binomial or binary logistic regression refers to the instance in which the observed outcome can have only two possible types (for example, "dead" vs. "alive"). Multinomial logistic regression refers to cases where the outcome can have three or more possible types (e.g, "better" vs. "no change" vs. "worse"). In binary logistic regression, the outcome is usually coded as "0" and "1", as this leads to the most straightforward interpretation. Like other forms of regression analysis, logistic regression makes use of one or more predictor variables that may be either continuous or categorical data.

Simulated data from the SEQ Water Grid model was used to estimate the coefficients of the regression model. Four levels of each variable (rainfall, demand and storage) were considered for estimating the coefficients of the regression model.

Statistical analytical software SPSS was used for carrying out logistic regression analysis. Using the coefficients obtained, probability of failure for any desired conditions of rainfall, storage and demand can be predicted.

4.4 DATA COLLECTION

For development of the SEQ Water Grid model, data and information on catchments, storages and treatment plants of the SEQ Water Grid had to be collected. The data was obtained from SEQ Water (one of the responsible authorities that manage the SEQ Water Grid). The necessary climate data (required for running the model) were obtained from the Bureau of Meteorology and the flow data were obtained from Department of Environment and Resource Management (DERM). Bureau of Statistics data sources were used for obtaining population data for current and future demand prediction.

4.5 SUMMARY

A critical review of research literature was used as guidance for selecting the requirements and conditions such as resilience characteristics, failure criteria, indicators and a surrogate measure, which were needed to be defined for this study. These definitions were used for developing an approach as the foundation for the resilience assessment process.

Evaluating the results of the modelled system was used as the basis for assessing the resilience of a water supply system. A large and complex water supply system (SEQ Water Grid) selected as the case study and was modelled using system dynamics modelling software (STELLA), enabling evaluation of simulated results under different pressure scenarios. This software was selected considering its high performance capability and ease of use.

Chapter 5: Case Study Area

5.1 BACKGROUND

Simulation of a water supply system was identified as the most practical method for evaluating its resilience. For this purpose, a suitable real-world water supply system was selected as a case study. The criteria for selecting a water supply system were discussed in Chapter 4 and the South East Queensland water supply system (SEQ Water Grid) was selected. One of the primary criteria for selecting the SEQ Water Grid as the case study was to emphasise the feasibility of applying resilience as a management concept for a complex infrastructure system.

SEQ Water Grid is a diverse system of water reservoirs and treatment facilities with an interconnecting network of water pipelines. However, the complete SEQ Water Grid still consists of the basic elements of a typical water supply system including catchment, water storage, treatment, as well as bulk and retail distribution. The complexity of the SEQ Water Grid compared to a conventional water supply system is in the interconnectivity of the multiple storage reservoirs and treatment plants enabling water transfer from one region to another. As the SEQ Water Grid catchments are located across a large area, hydrologic and climatic variation across the system is also influential. The influence exerted by factors associated with climate change as discussed in Chapter 3 are also critical for the SEQ Water Grid.

This chapter discusses the SEQ Water Grid in detail including current and potential population growth that will influence water demand in the service area and the characteristics and capacities of basic elements for highlighting climatic differences.

5.2 WATER SUPPLY IN SOUTH EAST QUEENSLAND

The SEQ region covers 22,420 km^2 and incorporates ten Local Government Areas, of Sunshine Coast, Moreton Bay, Logan, Gold Coast, Redland, Brisbane, Somerset, Lockyer, Ipswich and Scenic Rim. These local government areas are collected into five zones as SEQ Central, SEQ South, SEQ North, Redland and Scenic Rim as shown in Figure 5.1 for water supply administration purposes.

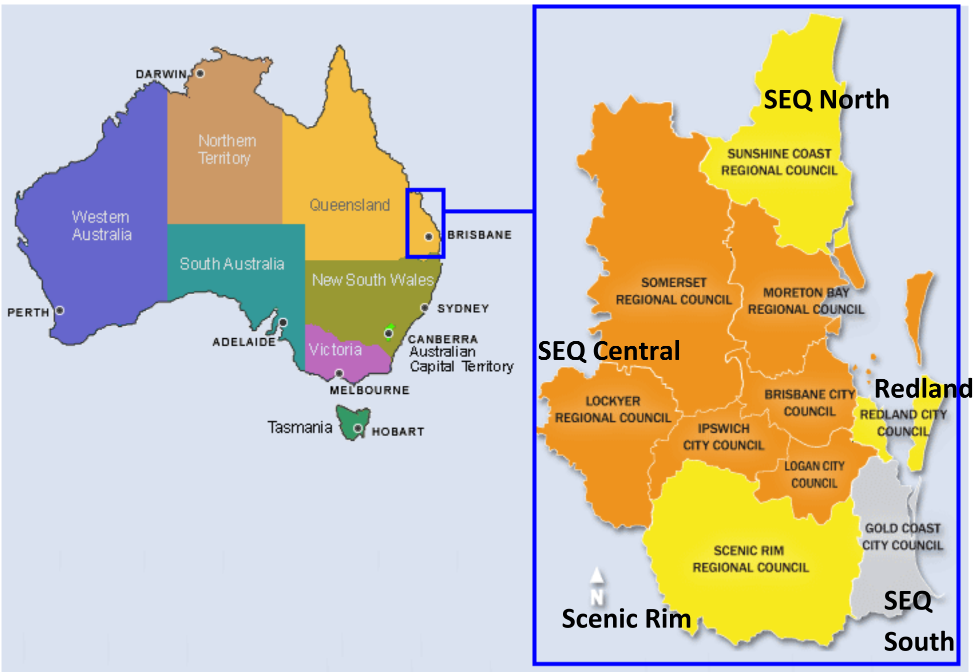


Figure 5.1 – South East Queensland
Adapted from http://feww.wordpress.com/category/environmental disaster

Potable water supply to SEQ region is an important issue due to the relatively high population density compared to the other parts of the country (Figure 5.2) and the rapid population growth in the region. Figure 5.2 shows that the population density in many parts of SEQ region is 100 or more per km^2, which is much higher compared to the other parts of Australia. Figure 5.3 further illustrates that according to 2001 to 2011 projections, most parts of SEQ will have high population growth rates resulting in a significantly high population by 2021.

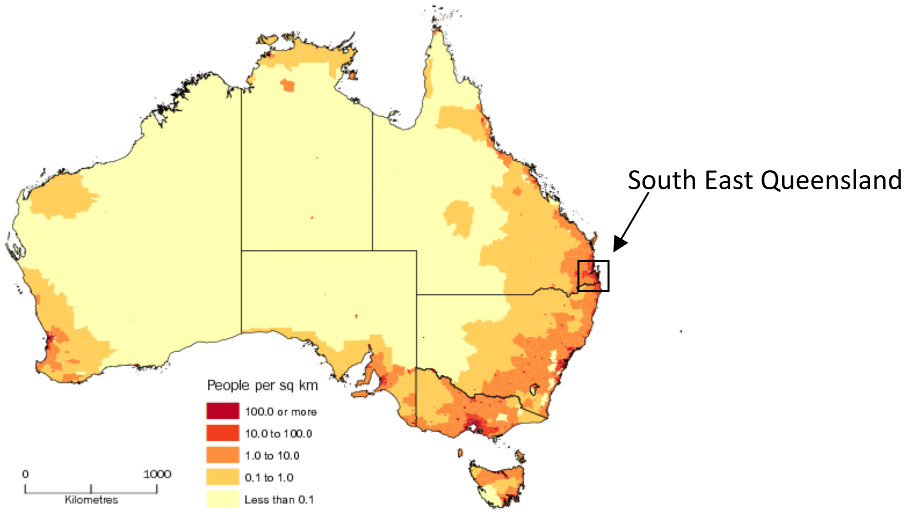


Figure 5.2- Population density in SEQ compared to other parts of Australia (adapted from Bureau of Stastics 2013)

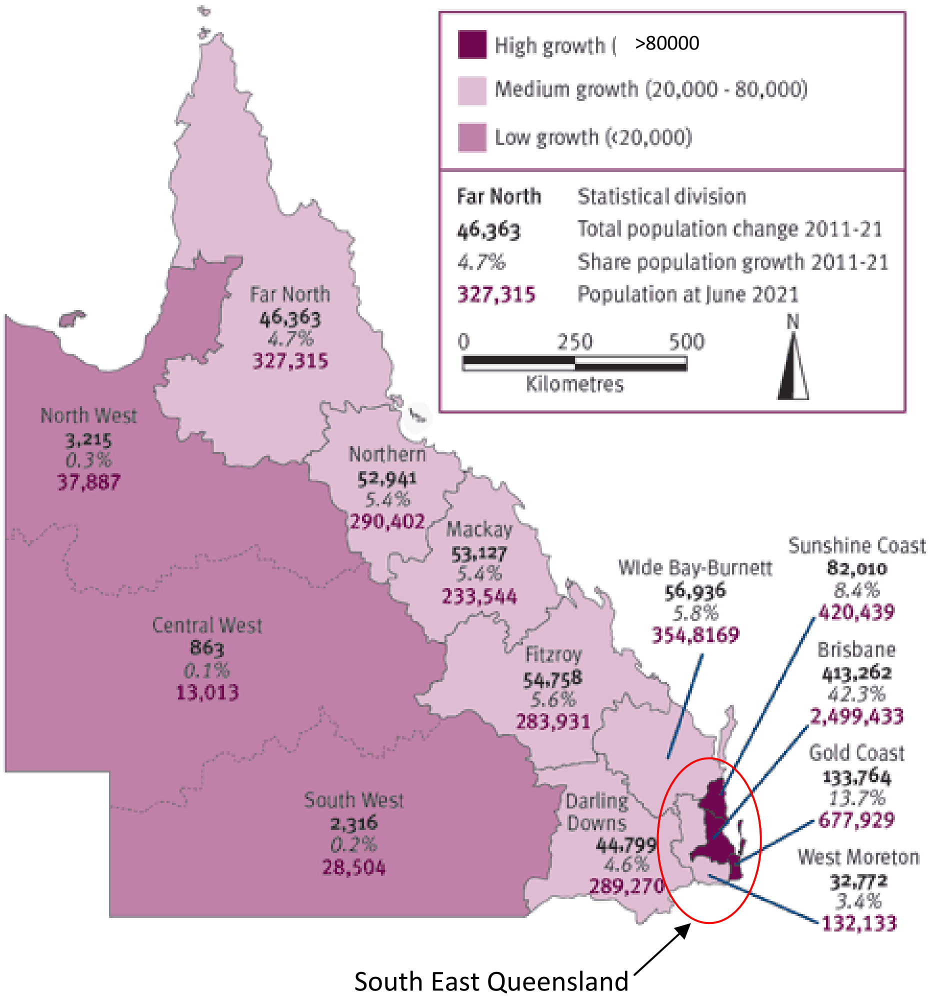


Figure 5.3- Estimated population change in SEQ from 2011 to 2021 (adapted from Queensland Government- Queensland Treasury and Trade 2013)

In South East Queensland, the population is based primarily in the Greater Brisbane area which recorded the fourth highest growth among the Australian capital cities in the five years June 2007 to June 2012, increasing by 233,200 people. Within Greater Brisbane, the Statistical Area of Ipswich experienced the largest growth in the five years to June 2012 (up 43,200 people), while Moreton Bay - South had the fastest growth of 18% (Bureau of Statistics 2013). As SEQ population continues to grow, forecasts show that the projected population in 2056 will be between 5,696,300 (medium series) and 7,014,700 (high series) (Queensland Water Commission 2010).

With a view to ensuring reliable potable water supply to satisfy current and future demand, the water supply systems were restructured by the State Government. As a result of this, South East Queensland Water (Restructuring) Act 2007 came into effect in 2007 and delivered major reform in the management of water services in South East Queensland. Under these reforms, a regional water grid was established to improve the capacity to transfer water amongst regional urban centers and a new institutional framework was set up. Accordingly, the SEQ Water Grid was established as a regional water supply system. The SEQ Water Grid commenced operation on 1st July 2008 (Engineers Australia, 2010). SEQ Water Grid is one of the largest water supply systems in Australia. The Water Grid was selected as the case study for this research project. The reasons for selecting the SEQ Water Grid as the case study were discussed in Section 4.2.2. The key elements and the features of the SEQ Water Grid are detailed in the following sections.

5.3 SEQ WATER GRID AND THE SERVICE AREA

SEQ Water Grid's capacity is about 350,000 ML/a compared to current demand of about 290,000 ML/a (Spiller et al. 2011). The major supplies for the SEQ Water Grid are from surface water sources which convey and store water using reservoirs and weirs. Therefore, the key elements of the system include service catchments, reservoirs and weirs and treatment plants. SEQ Water Grid which consists of multiple sets of infrastructure systems at regional level and interconnector pipelines provide connectivity between different regions. Apart from these, the Water Grid includes a desalination plant and the Western Corridor Recycled Water Project in addition to three advanced wastewater treatment plants. The locations of reservoirs, desalination plant, advanced water treatment plants and interconnectors are shown in Figure 5.4.

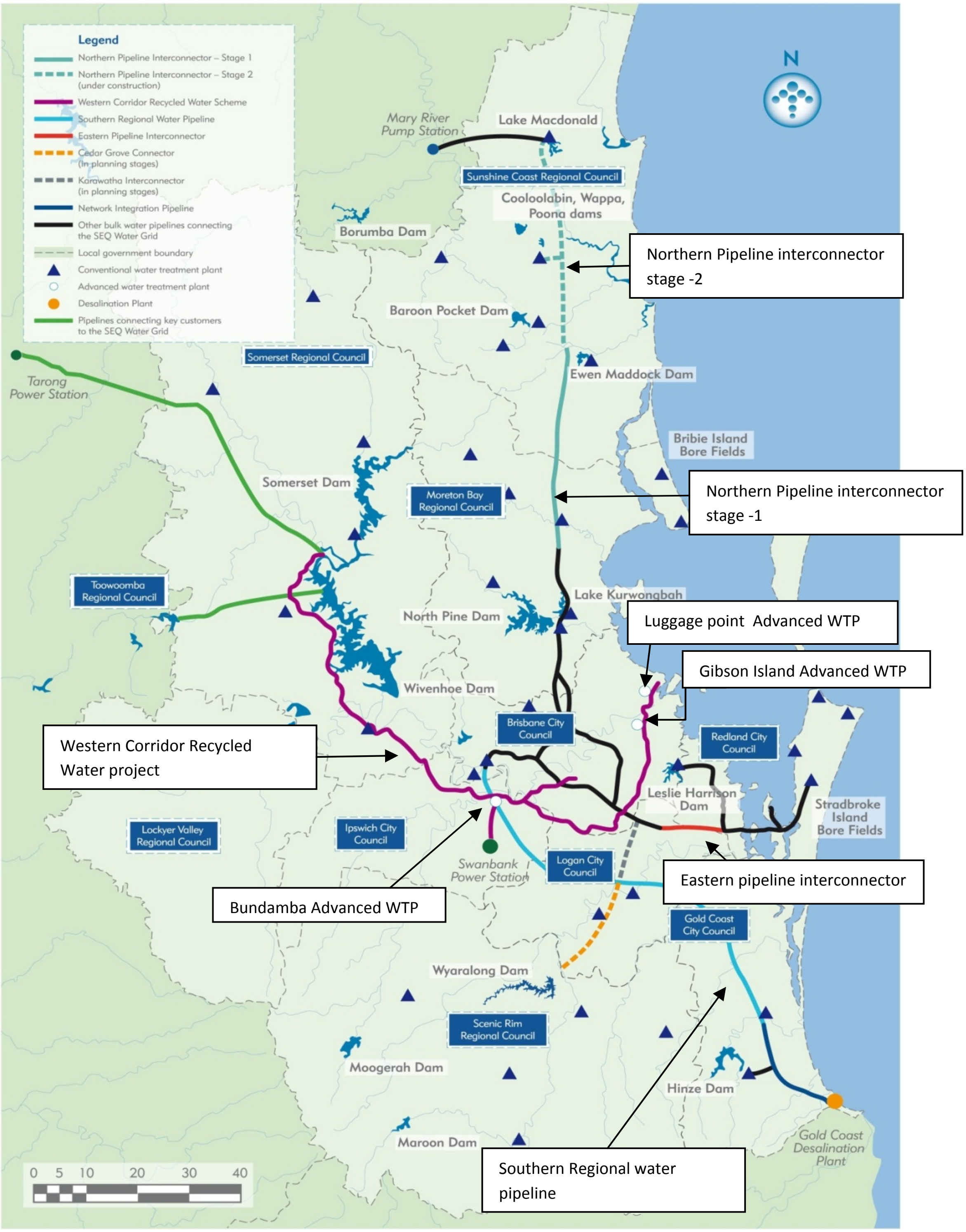


Figure 5.4- Main storage locations and the interconnector pipelines of SEQ Water Grid (adapted from http://seqwgm.qld.gov.au/seq-water-grid-operations/about-the-water-grid/connected-assets)

The SEQ Water Grid consists of 12 main catchment/storage reservoir/treatment plant subsystems (SEQ Water Grid Manager 2010). Among these 12 subsystems, Brisbane River subsystem, including Wivenhoe/Somerset reservoirs, is the largest contributor to the SEQ Water Grid. In the Brisbane river system, Somerset Dam is located on the Stanley River, a tributary of the Brisbane River. Water from the reservoir formed by Somerset Dam is released to Wivenhoe reservoir - the region's major storage. From Wivenhoe reservoir, water is released down the Brisbane River to Mount Crosby Weir, from where it is pumped to Mount Crosby East and West treatment plants. Other treatment plants of the Wivenhoe/Somerset system are Lowood, Woodford, Esk and Somerset dam water treatment plants.

The second largest contributor to the SEQ Water Grid is the storage reservoir formed by Hinze dam situated across Nerang River, in the Gold Coast region. The other storage reservoir in the Gold Coast area is the one created by Little Nerang dam which is located on Little Nerang Creek. The main treatment plants attached to these two dams are Mudgeeraba and Molendinar water treatment plants.

North Pine catchment and the reservoir (Lake Samsonvale) located on North Pine River near Petrie is the third largest supply source of the SEQ Water grid, which supplies water to North Pine water treatment plant. The reservoir created by the Baroon Pocket dam located near Maleny on Obi Obi Creek (a tributary of the Mary River) is the fourth largest reservoir among the SEQ supply sources. The reservoir provides raw water to the Lander's Shute and Maleny water treatment plants.

Leslie Harrison dam forms another reservoir which supplies water to Capalaba water treatment plant and Moogerah and Maroon dams form reservoirs that supply water to Boonah-Kalbar, South Maclean, Beaudesert, Kooralbyn, Rathdowney and Canungra water treatment plants. Ewen Maddock, Cooloolabin, Lake MacDonald and Wappa dams forms reservoirs those supply water to Ewen Maddock, Image Flat and Noosa water treatment plants and Lake Kurwongbah supplies water to the Petrie water treatment plant. The major infrastructure elements of the SEQ Water Grid discussed above are divided into five different zones for administrative purposes as shown in Figure 5.1. The reservoirs located in each zone and the local government areas, relevant treatment plants and their capacities are given in Table 5.1.

Table 5.1- Reservoirs and relevant treatment plant capacities of SEQ Water Grid

Zone	City Councils	Reservoir/ Weir	Reservoir Capacity (ML)	Treatment plants and capacities
SEQ North	Sunshine coast	Baroon Pocket	61,000	Landers Shute WTP (130ML/d) Maleny WTP (2.2ML/d)
SEQ Central	Brisbane Ipswich Lockyer Logan Moreton Bay Somerset	Ewen Maddock	16,587	E.M WTP (20ML/d)
		Cooloolabin	13,800	Image Flat WTP (18 ML/d)
		Wappa	4,694	
		Lake Mac Donald	8,018	Noosa WTP(30ML/d)
		Wivenhoe	1,165,238	Mt Crosby East, west (916ML/d) Lowood WTP (20ML/d)
		Somerset	379,849	Woodford WTP (20ML/d) Esk WTP (0.8 ML/d) Somerset Dam WTP(0.5ML/day)
		North Pine	214,302	N.P WTP (220ML/d)
		Lake Kurwongbah	14,370	Petrie WTP (45ML/d)
		Caboolture weir		Caboolture WTP(14ML/D)
Redlands	Redlands	Leslie Harrison	24,868	Capalaba WTP (18ML/d)
Scenic Rim	Gold coast	Moogerah	83,765	Boonah Kalbar WTP (3.5ML/d)
		Maroon	45,319	South Maclean WTP (11ML/d) Beaurdesert WTP (4.8ML/d) Kooralbyn WTP (1.9ML/d) Rathdowney WTP (0.4ML/d) CanungraWTP(0.6ML/d)
SEQ South	Gold Coast	Little Nerang	6,705	Mudgeeraba WTP (100ML/d) Molendinar WTP (165ML/d)
		Hinze	310,730	

Apart from the regular surface water supply subsystems, two major water supply infrastructure components are connected to the SEQ Water Grid. These are the desalination plant at Tugun, Gold Coast and the Western Corridor Recycled Water Project. The desalination plant at Tugun operates as an emergency supply source for producing desalinated water during the low storage levels in major reservoirs. It is capable of providing up to 133 ML of water a day. A 25 km pipeline connects the plant to the South East Queensland Water Grid. As a measure of reducing operational cost, the plant operates in standby mode and returns to full capacity operation only when the region's reservoir capacity drops to 60%. Desalination is considered a climate-resilient supply source. However, the production cost is comparatively high.

The Western Corridor Recycled Water Project is a part of SEQ Water Grid that includes three advanced water treatment plants at Bundamba, Gibson Island and Luggage Point and more than 200 km pipelines. It has the capacity to provide up to 232 ML of purified recycled water per day. Although the bulk of the treated water is conveyed to power stations, industrial customers and agricultural users, it can also supplement the region's drinking water supply by recharging Wivenhoe Dam when dam levels fall below 40%.

One of the key features of the SEQ Water Grid is its ability to transfer water from surplus areas to areas in deficit. A total of 22 bulk water pump stations and 535km potable bulk water mains strengthen the distribution capacity of the SEQ Water Grid. The Water Grid is capable of transferring an average of 600ML/d, to where the water is needed most (Link Water 2012). Transferring water is facilitated by the interconnector pipelines across different regions. The three main interconnectors are:

- Southern Regional Water Pipeline;
- Northern Pipeline Interconnector; and
- Eastern Pipeline Interconnector.

More information about these interconnector pipelines is given below (Water Secure 2012).

The Southern Regional Water Pipeline is a 94 km two-way pipeline that moves water between the Gold Coast and Brisbane (see Figure 5.4). The pipeline can transfer water between Hinze Dam, Gold Coast Desalination Plant and Wivenhoe Dam. The capacity of the pipeline is 130 ML/d.

The Northern Pipeline Interconnector includes two stages; Stage 1 and Stage 2. Stage 1 is 47 km long and has the capacity to transfer 65 ML/d while Stage 2 is 48 km long with capacity to transfer 18 ML/d. Stage 1 pipeline connects Lander's Shute Water Treatment Plant to the Morayfield reservoir. Stage 2 continues from Lander's Shute Water Treatment Plant to the Noosa Water Treatment Plant (see Figure 5.4).

The Eastern Pipeline Interconnector is a bulk water transfer pipeline that can deliver up to 22 KL/d to the water grid. The pipeline links Leslie Harrison Dam with Logan (see Figure 5.4).

The above features of the SEQ Water Grid give a high degree of connectivity between different zones and additional capability to operate efficiently during water stress events. Prior to the construction of the SEQ Water Grid, restrictions were frequently applied in some parts of the region, while reservoirs in other parts were full or overflowing. For example, during the drought that commenced in the year 2000 in regions across Australia (Millennium Drought), the water supply in Brisbane's reservoirs fell below 17%, while Gold Coast reservoirs were overflowing (Spiller et al. 2011).

5.4 CATCHMENT CHARACTERISTICS AND CLIMATIC CONDITIONS

As the SEQ grid area is a comparatively large area, the water supply catchments located at the fringes are subjected to significant differences in catchment and climate conditions. This section provides a discussion of the differences in catchment and climate conditions within the region.

The key differences in catchment characteristics include different catchment sizes, land use patterns, topography, soil types and different types of vegetation. The significance of these differences for this study is the influence on catchment hydrology. Due to the differences in the characteristics, the fraction of rainfall converted to runoff differs across catchments. The fraction of rainfall converted to runoff can be estimated by using a runoff coefficient. The runoff coefficient accounts for rainfall losses. Use of a runoff coefficient is a simplistic and lumped approach, but is commonly used. Differences in runoff coefficients indicate the dissimilarities of different catchments. A detailed discussion about the derivation of runoff coefficients is given later in the thesis.

The key difference in influential climatic conditions is due to differences in rainfall patterns and distributions across the region. The average annual rainfall, monthly rainfall variation and temporal variability are important considerations to understand the dissimilarities in climatic conditions in different catchments. These parameters show the influence of rainfall variability on stream flow.

Based on the closest Bureau of Meteorology (BOM) rain gauge station to each of the relevant reservoirs, average annual rainfall variability from 1997-2011 is tabulated in Table 5.2. SEQ Northern and SEQ Southern catchments have had high annual rainfall compared to the SEQ Central catchments, demonstrating variability in rainfall at a broad level.

Table 5.2 - Catchment areas, average annual rainfall between1997-2011 and relevant BOM rainfall gauging station numbers

Zone	Dam	Catchment area (Km^2)	Average annual rainfall (mm) (1997-2011)	BOM gauging station number
SEQ North	Baroon Pocket	72.00	1754.78	040850
	Ewen Maddock	21.00	2211.83	040759
	Cooloolabin	8.10	1674.19	040757
	Lake Macdonald	49.00	818.84	040115
	Wappa	69.70	1395.00	040525
SEQ Central	Wivenhoe	7020.00	712.15	040763
	Somerset	1340.00	919.07	040189
	North Pine	348.00	1110.84	040186
	Lake Kurwongbah	53.00	1199.71	040633
Redlands	Leslie Harrison	87.00	1102.31	040458
Scenic Rim	Moogerah	228.00	927.77	040135
	Maroon	106.00	862.88	040677
SEQ South	Little Nerang	35.20	1659.06	04052
	Hinze	207.00	1352.74	040584

Figure 5.5 shows the average monthly rainfall pattern for each catchment, determined from the 1997-2011 monthly rainfall data obtained from the Bureau of Meteorology. It can be observed that the rainfall distribution pattern over a year is similar in all catchments, having maximum rainfall around February and minimum around July. However, for any particular month, there are notable differences in the rainfall in terms of rainfall depth in different catchments.

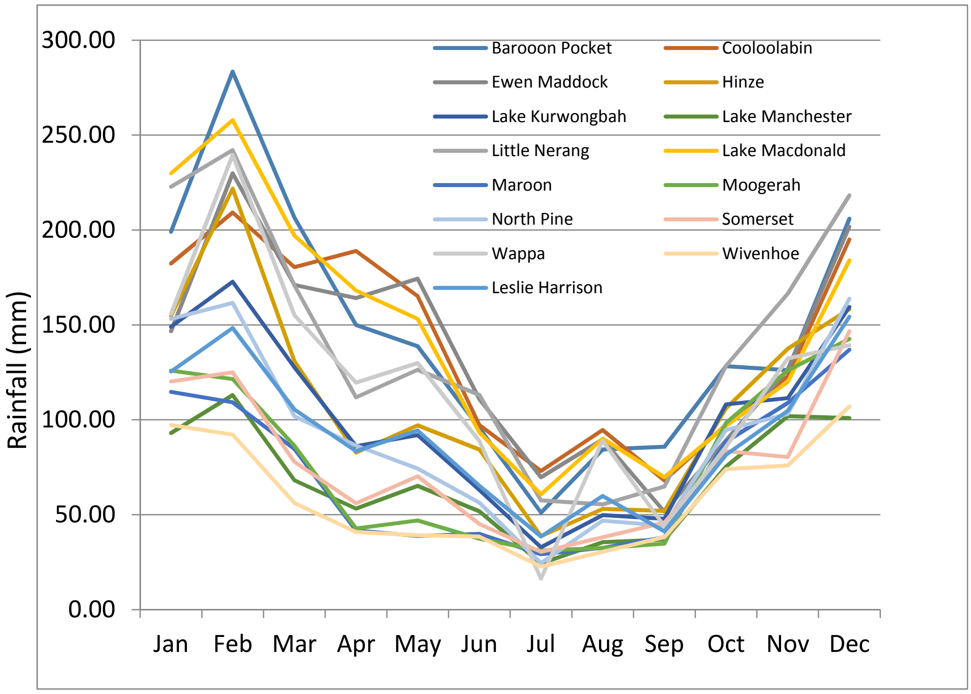


Fig 5.5- Average (1997-2011) monthly rainfall in different SEQ catchments

Considering temporal variability, the annual rainfall in South East Queensland has shown considerable variability over the years. Variability of annual and seasonal rainfall is illustrated in Figure 5.6.

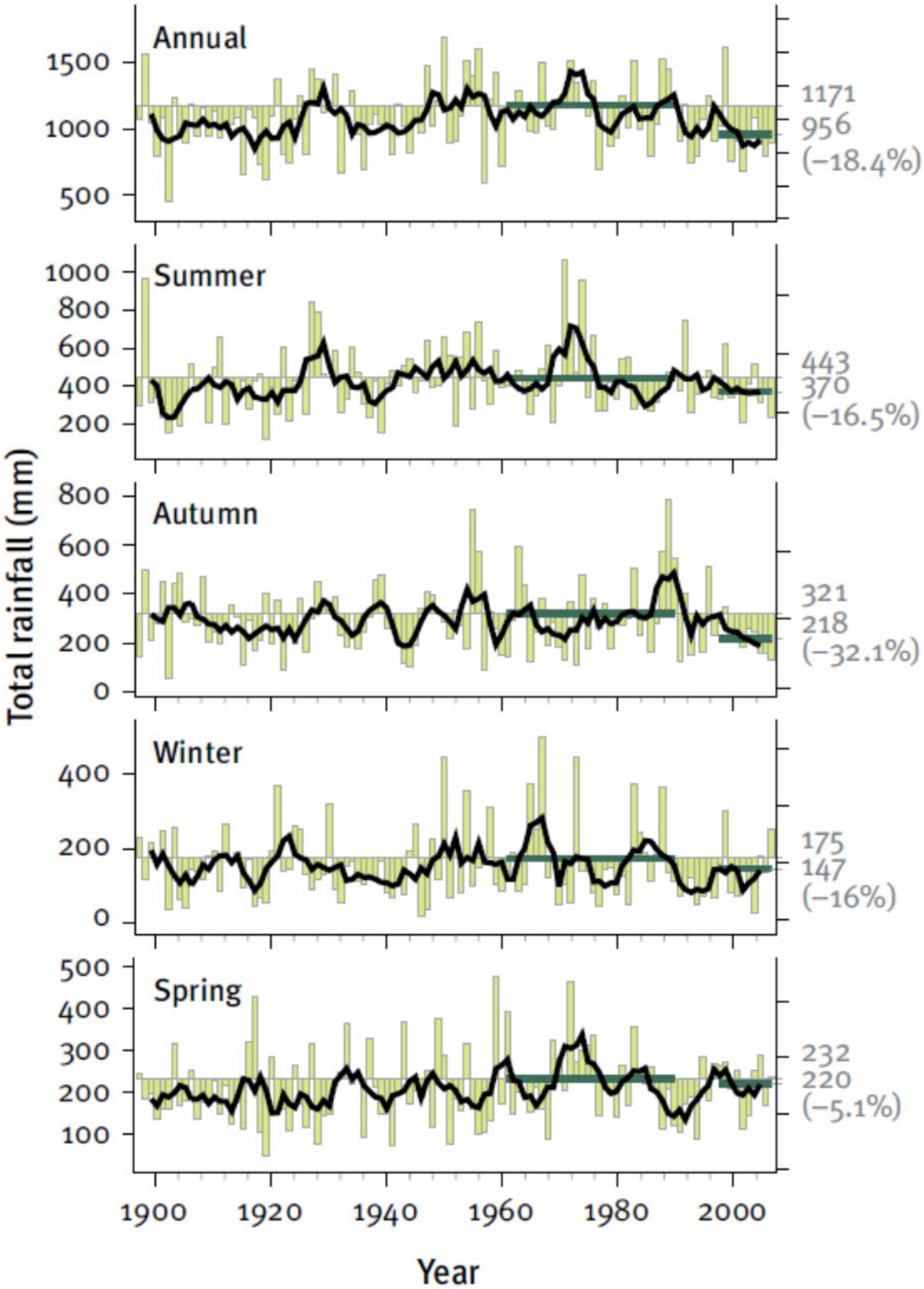


Figure 5.6- Historical annual and seasonal total rainfall for the SEQ region for the period of 1900 – 2010 (adapted from Queensland Government 2012)

Figure 5.6 shows the five-year running average of total rainfall for different seasons in SEQ. The mean values for the period 1961-1990 and for the decade 1998-2007 are shown by the green lines. The numerical values for the same are indicated at the right vertical axis of the graph. The difference in rainfall between the baseline and last decade is shown in brackets. Accordingly, the average annual rainfall over the last decade has decreased by 18.4 percent compared to the 1961-1990 average. This provides an indication of the trend in rainfall over the years.

The facts highlighted above show that the water catchments that contribute to the SEQ Water Grid have similarity in terms of the distribution pattern of rainfall, in terms of rainfall depth over a year and differences in average annual rainfall, monthly rainfall variability and temporal variability. The differences in rainfall distribution formed the basis for developing a regional water supply system such as the SEQ Water Grid, enabling water transfer between zones.

The difference in climatic conditions within the region is expected to widen further in the future due to climate change. The SEQ region is expected to experience low rainfall, higher temperature and higher evaporation under high, medium or even low Greenhouse Gas emission scenarios as per the predictions of the Queensland Government (2012), as shown in Table 5.3. This decreasing trend of rainfall due to climate change has the potential to increase stress on the SEQ water supply system and hence reduce system resilience.

Table 5.3- Temperature, Rainfall and Evaporation projections for SEQ under climate change (adapted from Queensland government 2012)

Variable	**season**	**(1971-2000)**	**2030**	**2050**		**2070**	
			Emission Scenarios				
		Current historical mean	**Medium**	**Low**	**High**	**Low**	**High**
			Projected changes				
Temperature ^{0}C	Annual	19.4^{0}C	+0.9	+1.1	+1.8	+1.5	+2.9
	Summer	23.9^{0}C	+0.9	+1.1	+1.7	+1.5	+2.8
	Autumn	20.1^{0}C	+0.8	+1.0	+1.7	+1.4	+2.7
	Winter	14.0^{0}C	+0.9	+1.1	+1.8	+1.5	+2.8
	Spring	19.6^{0}C	+0.9	+1.1	+1.9	+1.6	+3.0
Rainfall %	Annual	1135mm	-3	-3	-5	-4	-8
	Summer	431mm	0	-1	-1	-1	-1
	Autumn	317mm	-3	-3	-5	-4	-8
	Winter	148mm	-5	-6	-10	-8	-15
	Spring	227mm	-5	-6	-9	-8	-15
Potential Evaporation %	Annual	1553mm	+3	+3	+6	+5	+10
	Summer	522mm	+3	+2	+6	+5	+10
	Autumn	334mm	+4	+4	+7	+6	+11
	Winter	241mm	+4	+4	+7	+6	+12
	Spring	458mm	+3	+3	+6	+5	+9

5.5 SUMMARY

In order to evaluate the applicability of the concept of resilience in the development of management strategies for enhancing the effectiveness of service delivery of a large water supply system, the SEQ Water Grid was selected as the case study. The SEQ Water Grid is one of the largest water supply systems in Australia consisting of multiple storage and treatment facilities, interconnection pipelines and a desalination plant as an additional supply source. As the storage reservoirs are located over a large area in South East Queensland, the climate conditions are different in different catchments. Furthermore, characteristics of different catchments also vary. Water demand is an increasing trend since South East Queensland is a fast growing region.

Chapter 6: System Modelling

6.1 BACKGROUND

Different approaches are used in catchment hydrology and water resource modelling. Brunsell (2012) noted that models are used for testing existing systems with a view to supporting design and decision making processes. The type of modelling approach depends on the intended purpose. Accordingly, different modelling concepts and software are used. For example, hydrologic and hydraulic modelling approaches are effectively used for flood analysis.

System Dynamics (SD) is a powerful modelling technique where incremental adjustments can be incorporated into models of complex systems and processes. Hence, SD was used in this study for modelling the SEQ Water Grid for evaluating the resilience of water supply systems. The modelling tool used was STELLA. Selection of the STELLA software, and key characteristics of the software, was discussed in Chapter 4 and characteristics of the selected study system which was modelled (SEQ Water Grid) were discussed in Chapter 5.

This chapter discusses the fundamentals of system dynamics modelling and the model development procedure adopted to develop the SEQ Water Grid model. Considerations for model development at different stages in relation to the SEQ Water Grid are discussed in detail. Relevant equations were used to derive input data where necessary. The problems encountered when developing the SEQ Water Grid model are also discussed in this chapter.

6.2 SYSTEM DYNAMICS MODELLING

A base level understanding of the system dynamics modeling was required for developing the SEQ Water Grid model which is discussed below. Different researchers have interpreted the importance of the system dynamics technique in different terms. The following two interpretations by past researchers given below help to understand the use of systems dynamics modelling in the context in which it was used in this research study:

- System dynamics is a framework for identifying interrelationships and patterns of change rather than static snapshots, and for identifying processes rather than objects (Simonovic and Fahmy 1999).

- System dynamics is a set of techniques for thinking and computer modelling that helps practitioners to understand complex systems such as, for example, the human body or the national economy or the earth's climate. System tools help to keep track of multiple interconnections and they help to show things holistically (Fuches 2006).

Furthermore, system dynamic modelling provides an intuitive approach to the modelling of dynamic systems in any field in a simple manner (Fuchs 2006). Saysel *et al.* (2002) noted that the key purpose of system dynamics modelling is to inform developmental improvements in managerial decision making and policies. This has a direct applicability to this study where the dynamics of a water supply system was the main focus.

In modelling the complete water supply system, determining the interrelationships between key factors is a complex process. Therefore, when using conventional techniques for modelling systems with interrelated processes, more than one modelling tool may be required for building a single model. In the case of a water supply system, this may include a catchment hydrology model, stream flow hydraulics model and a water storage model. This significantly increases the complexity of the modelling procedure. Sivapalan (2005) further acknowledged this complexity in noting that even the best hydrologic and hydraulic models are often found to be inadequate to predict catchment responses since they demand comprehensive knowledge of climate inputs and landscape characteristics such as soils and vegetation, which are not routinely available.

However, as this study was focused on highlighting the importance in understanding variations in system behavior with respect to the pressures applied on the system rather than evaluating hydrologic characteristics of a catchment, it did not require the derivation of outcomes that an in-depth catchment hydrologic model would be required to provide. Instead, the generic response of the system to selected key input variables was considered appropriate for the assessment of system behaviour. In this regard, the important concern was to identify the interdependencies and the relationships between different subsystems of the water supply system, so that the complete model was able to undertake appropriate simulations for varying input conditions. Accordingly, the purpose of developing the SEQ Water Grid model was to undertake simulations under different pressure scenarios and thereby to understand the system capabilities that in turn would allow the formulation of proactive management strategies.

Similar applications of system dynamics modelling in research literature informed the type of system dynamic models to be used and common purposes of its usage. Tangirala *et al.* (2003) used system dynamics modelling to develop a simulation model for evaluating the total maximum daily load allocation in a nutrient impaired stream. Stave (2003) developed a model to simulate different scenarios to evaluate water supply problems in Las Vegas, Nevada. Elmadhi *et al.* (2007) developed a model to examine the possible options for re-allocating water resources to minimise the water cost in an irrigated area. Gurung (2007) developed three models to analyse the process of eutrophication of a river. A common objective of the modelling undertaken in these studies was to evaluate a complex system under different operating conditions with a view to formulating effective management strategies. The models used in the above-mentioned studies provide evidence of successful use of system dynamics modelling in applications, similar to what was required in this study for the simulation of different scenarios.

6.2.1 Simplified architecture of system dynamics modelling

The output of a system dynamics model is typically obtained by simulating different input scenarios. Simulations of future scenarios help to strengthen the ability to comprehend future system states. As long as the model describes reality at the required level of accuracy, the modelling process and its outcomes can be used to improve the understanding of systemic behaviour as a necessary step towards managing change in large scale systems effectively. Morecroft (1992) further emphasised that systems modelling and simulation can support policy analysis and evaluation.

Dynamic simulation models primarily consist of mathematical equations describing the functions of the system through time and space. Based on these equations, when the system state and conditions are known at a point in time, the system state and condition at the next point in time can be determined. Repeating these processes, the system behaviour can be simulated through step-wise progression over any desired time period. A simple model used to demonstrate the dynamic simulation process as illustrated by Fuchs (2006) is shown in Figure 6.1.

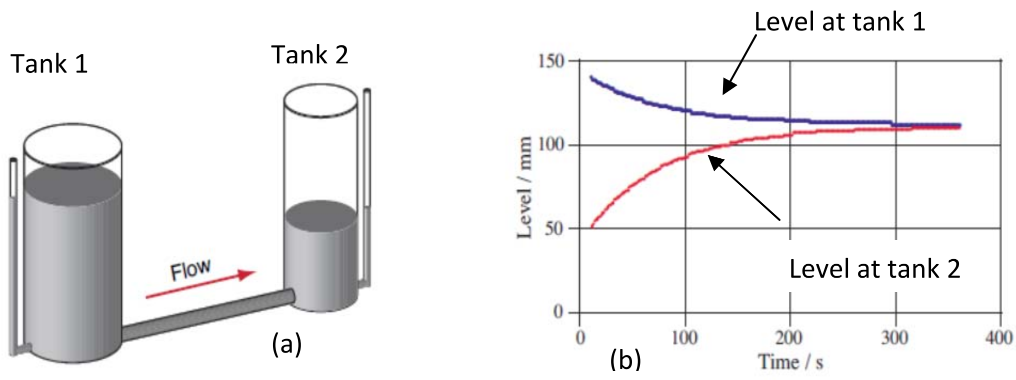


Figure 6.1- Dynamic behaviour of two connected tanks (adapted from Fuchs 2006)

Figure 6.1(a) shows two tanks containing a liquid connected by a pipe at the bottom. The liquid levels in the two tanks are as shown in Figure 6.1(a) at time zero and varies with time as shown in Figure 6.1(b). In Figure 6.1(b), the blue and red lines indicate the level of Tank 1 (which had more liquid at the beginning) and the level of Tank 2, respectively. During the initial periods of the operation, the levels change at a faster rate. The rate of change in water level reduces with time and the flow through the pipe stops when the levels in the two tanks are equal.

Relating this to a segment of a water supply system, the first tank can be considered as the catchment where the amount of water in the tank is the result of a rainfall event. The second tank can be considered as the reservoir. The flow through the pipe can be an analogue of the runoff in the connecting stream. Assuming that the peak flow starts immediately, flow to the reservoir will start at a faster rate and eventually stop when stability occurs. However, in reality the catchment/reservoir system and the modelled two tank system act in different ways in stabilising. Flow between the two tanks stops when the water levels become equal and the flow depends on the difference in hydraulic head between the two tanks. The flow from the catchment to the reservoir stops when there is no excess water in the catchment available to flow into the reservoir.

Runoff generation in a catchment involves processes dependent on catchment characteristics such as area, topography, soil type and climatic conditions such as rainfall characteristics and temperature. This involvement of a range of variables makes runoff generation a complex process. This complexity leads to the need to utilise a range of mathematical equations to investigate the interrelationships between input data.

Having identified the interrelated operations of a system, an important step in system dynamics modelling is the development of a Causal Loop Diagram (CLD). A causal loop diagram is a diagram that helps in visualizing how the interrelated variables affect one another. The causal Loop Diagram represents the relationships between the elements in the model. The diagram consists of a set of nodes representing the variables connected together.

There are two types of relationships. They are the relationships that can be represented by a positive feedback loop or a negative feedback loop (Proust and Newell 2003) as shown by the example given in Figure 6.2.

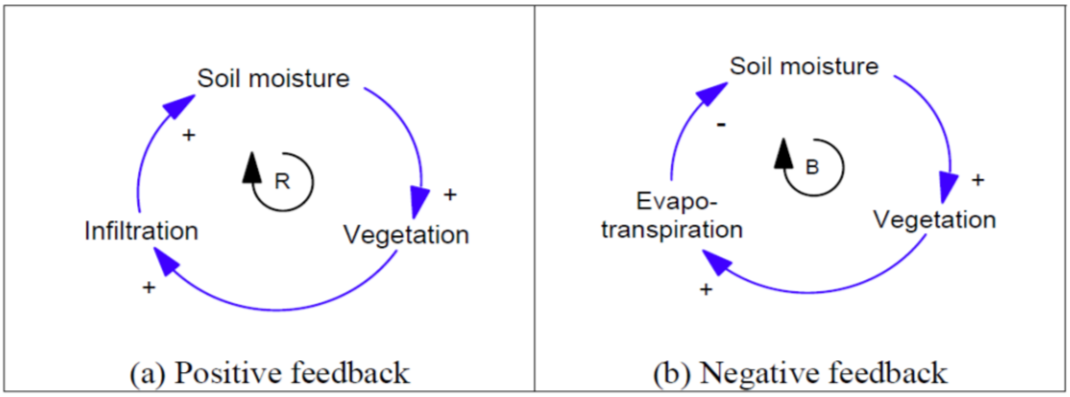


Figure 6.2 -Positive and negative feedback loops (adapted from Proust and Newell 2006)

A ***positive*** feedback is one in which a change (increase or decrease) in a variable results in the same type of change (increase or decrease) in a second variable. Positive feedback occurs in a feedback loop when the mathematical sign of the net gain around the feedback loop (sometimes called the *loop gain*) is positive. Positive feedback is a process in which the effects of a small disturbance in a system can include an increase in the magnitude of the perturbation. Positive feedback tends to cause the system to be unstable. A ***negative*** feedback is one in which a change (increase or decrease) in one variable results in the opposite (decrease or increase) in a second variable. Negative feedback tends to balance the processes of a system (Madani 2009).

Figure 6.2(a) indicates the relationships between soil moisture, vegetation and infiltration. All variables are related positively, making the feedback loop positive. In Figure 6.2(b), the negative relationship between soil moisture and evapotranspiration (one decreases as the other increases) makes the feedback loop negative.

6.3 MODEL DEVELOPMENT

System dynamics modelling commonly involves four essential stages as listed below (Albin 1997):

1. Conceptualisation
2. Formulation
3. Testing
4. Implementation.

Those four stages include model development and steps for obtaining the final outcome. The model development that is discussed in this section included only the first two stages, namely, conceptualisation and formulation. Hence, these two stages are discussed in detail in the next sections.

6.3.1 Conceptualisation

The conceptualisation stage primarily aims to establish the complete system in a diagrammatic form. The basic conceptualisation of the SEQ Water Grid model was based on the three nested subsystems that form the components of the meta-system as discussed in Chapter 1. The three subsystems undergo different processes enabling the subsystem responses to be different even under similar pressure conditions.

The following steps were undertaken in conceptualising the SEQ Water Grid:

- Conceptualising the governing factors influencing the final outputs;
- Defining the objective of modelling;

- Identifying the model boundaries;
- Identifying the rate of output from the system;
- Developing the Causal Loop Diagram;
- Establishing the mechanism for changing the rainfall input;
- Undertaking the water balance analysis for the reservoir.

Each step is discussed in detail below.

Conceptualising the governing factors influencing the final outputs

The meta-system consists of a set of nested subsystems and the final output is influenced by processes in each subsystem. Each subsystem has a maximum output potential and the subsystem with the lowest maximum output potential plays the key role in determining the final output at any given time. Hence, the excess capacity in a particular subsystem may become redundant under normal operational conditions. Table 6.1 outlines how the lowest output potential of each of the subsystems has the potential to govern the final output of a water supply system.

Table 6.1 –Limiting conditions of each subsystem

Process (1)	→ **Facilitated by** (2)	**Output** (3)	**Conditions that may limit the output** **(limiting conditions)**	
Storage ↓	Storage capacity Inflow to reservoir	Available raw water volume	Storage capacity + Limited inflow	The lowest output potential will govern the final output
Treatment ↓	Treatment plant →	Treated volume	Treatment plant capacity	
Bulk Distribution	Pumping and transfer →	Transfer volume	Pumping, transfer and distribution reservoir storage capacity	

Each process in column (1) of Table 6.1 is facilitated by the relevant property/ component listed in column (2). The output of each process is given in column (3). The integration of the main processes shown in column (1) activates the entire water supply system. However, the purpose and the functions of the storage reservoir, treatment plant and the bulk distribution system are different. For example, the storage reservoir has to store water for low rainfall periods to meet the demand until the next adequate rainfall period. Assuming a repetitive rainfall pattern, the reservoir storage may be sufficient to satisfy at least one year's demand. The treatment plant is generally designed to supply water to meet the average demand. During low demand the treated water is stored, and this water storage will supply the additional water required during peak demand. The treated water storage has to account for short term demand variability (weekly or monthly). The bulk distribution system is designed to meet the average demand. During low demand, the water is stored in distribution reservoirs scattered throughout the distribution area so that the storage capacity can be used to meet the peak demand. The storage in distribution reservoirs is also required to account for short-term demand variability. The distribution pipelines are designed to meet the peak demand.

Due to the differences in the functions of the storage reservoir, treatment plant and bulk distribution system, the scale of the required capacities vary. The storage reservoir needs a relatively larger capacity, while the treatment plant and distribution system needs comparatively smaller operational capacities.

For smooth functioning of the entire system, sufficient output (column 3 of Table 6.1) should be provided by each process (column 1 of Table 6.1). Limitations in any of the processes will restrict the final output. Therefore, the maximum output potential at any given time in each subsystem is a governing factor for deciding the operational output of the overall system.

The conditions adopted for modelling were set as follows. The relevant treatment plant/s were allowed to obtain water only if the storage level in the reservoir was above 20% of the reservoir capacity. The 20% storage limit was set as the minimum operational volume. When the reservoir storage drops to a very low level, the concentration of suspended solids increases. This results in high turbidity and exerts an additional burden on a treatment plant. The maximum rate of extraction was limited to the maximum treatable rate of the treatment plant. In a typical water treatment plant, the capacity to treat varies, depending on quality of the water stored in the reservoir. This feature was not incorporated into this model due to the lack of relevant technical data to develop an appropriate relationship between treatment capacity and raw water quality. It was assumed however, that the treatment potential of the treatment plant reduces by 10% for high rainfall events (above the monthly average rainfall) due to degradation of raw water quality.

Defining the objective of modelling

A clear and strictly defined objective is important for determining the essential components that should be included in the modelling exercise. The purpose of modelling the SEQ Water Grid in this study was to understand the system behaviour under defined pressures. Systemic resilience can be highlighted by behaviour characteristics.

Identifying the model boundaries

Understanding the nature of the model boundary conditions is critical for the key decisions in relation to model development. In this study, the behaviour of the water supply system was evaluated under different rainfall conditions. Rainfall is the main source of water inflow in the system. Therefore, rainfall was a key boundary condition for modelling in this study. A reference level for rainfall was defined for evaluation.

The length of the simulation period was required to be selected so that the model response was sufficient to demonstrate the reaction to a pressure exerting event. Due to the differences in catchment characteristics, the rate of influence of the pressure differs. Therefore, in the case where the rainfall is a boundary condition, the simulation period has to comply with catchment behaviour, which incidentally requires the longest time to react to pressure events (low rainfall). It was assumed that a five-year period was of sufficient duration for stabilisation, after the pressure due to the occurrence of low rainfall. Accordingly, the simulation period was set for a five-year time period.

Typical water resource systems are simulated at monthly intervals. Monthly time step simulations are adequate to capture both long term and seasonal variations in rainfall. Hence, the evaluation of very short term (for example daily) rainfall data as model input may not provide a useful contribution. Accordingly, the (SEQ Water Grid) model was designed to simulate in monthly time steps.

Representative rainfall values for each catchment were selected from historical rainfall data. As the rainfall for the same month for different years can show a significant variation, the mean rainfall value for the same month for different years was not a representative rainfall for a typical month. Therefore, in order to input the data at a smaller scale, the mean of the logarithm of the rainfall value for the same month in each year was used as input data. The exponent of the logarithm of rainfall value was obtained by an additional inbuilt function available in the software.

A typical annual rainfall pattern was created and extended for a five year period. This typical monthly rainfall is referred to as 'average rainfall'. For obtaining the probabilistic output from the model, a normal distribution function was assumed for generating the rainfall data. This enabled the generation of different output for different simulations (stochastic simulation) and calculation of the probability of obtaining a specified level of output.

Identifying the rate of output of the selected system

From the baseline data obtained, the total (system) storage capacity of the system was determined to be 2,349,245 ML in 2010. The combined treatment plant capacity of the system is 52,973 ML/month. Therefore, based on the discussion about the governing factors influencing the final output, the operational volume at any given time was considered as the treatable rate of the treatment plants. Hence, the maximum operational output rate (100%) at any given time is 52, 973 ML/month.

Each of the interconnecting pipelines of the SEQ Water Grid has a maximum capacity. Hence, that could be a limitation for the most efficient distribution between regions. However, for this study, water distribution efficiencies were not considered as these factors were not directly related to this initial modelling exercise. It was assumed that the total treated water production is distributed efficiently.

Development of the Causal Loop Diagram

For developing the Causal Loop Diagram (CLD) for the SEQ Water Grid, firstly, the conceptual model of the system (SEQ Water Grid) was mapped. The complete Water Grid consists of 12 main reservoirs. Each reservoir forms a subsystem of a catchment, reservoir and treatment plant combination. Amalgamation of the 12 subsystems forms the complete Water Grid. Figure 6.3 indicates the schematic diagram illustrating the dams that contribute to the SEQ Water Grid that was modelled.

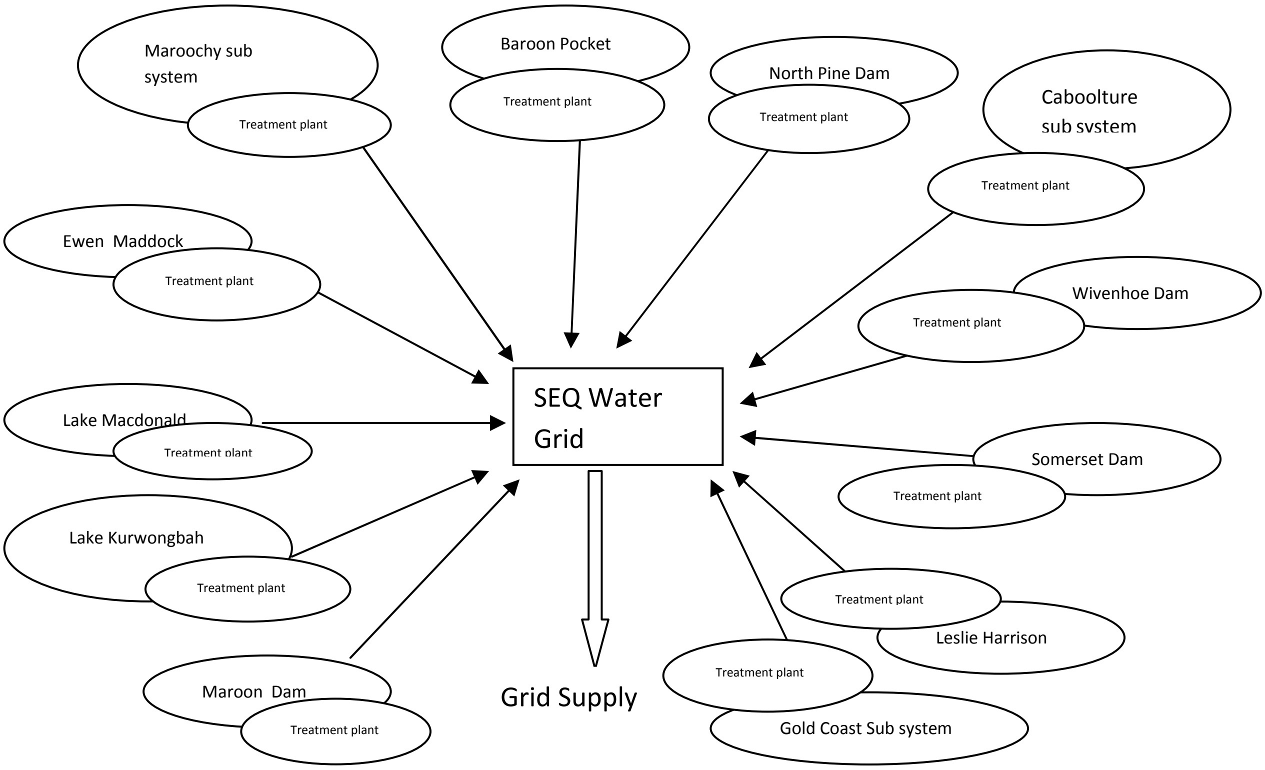


Figure 6.3- Schematic diagram of the SEQ Water

A single subsystem, consisting of a catchment, reservoir and treatment plant was initially considered for developing the CLD. The CLDs for all the subsystems have the same relationships, but different input data, as the properties and climate conditions vary in each catchment. The relationship adopted for developing the CLD for a single subsystem is discussed below.

At the catchment level, the main water inflow source is the rainfall. However, the amount of runoff generated depends on catchment properties such as area, shape, infiltration capacity, soil moisture and land use (Singh *et al.* 2009) and climate conditions (rainfall volume and intensity, temperature, evaporation, antecedent dry period). Only a fraction of precipitaion is converted into runoff. This fraction can be represented by a runoff coefficient. Therefore, volume of inflow is associated with the rainfall depth, catchment area and the runoff coefficient. The parameters linked with inflow are illustrated in Figure 6.4.

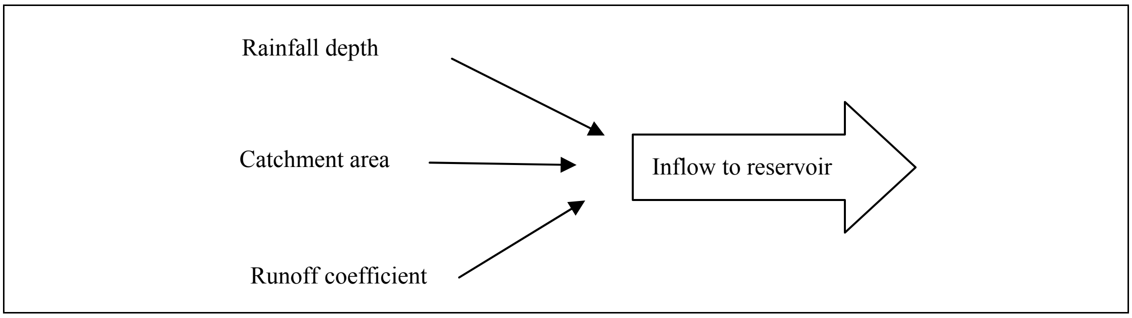


Figure 6.4 -Parameters linked with inflow

Mechanism for changing the rainfall input

As the storage reservoirs are located over a wide region, monthly rainfall across the catchments will vary. Therefore, rainfall data for each catchment was considered separately. However, it was assumed that *variation* of rainfall (increase or decrease) due to future climate scenarios with respect to the average rainfall for all the catchments is similar. Therefore, a single incremental factor was connected to an input rainfall converter (entity of the model that facilitates data input) for all the catchments. The increase or decrease in rainfall for the entire region (all the catchments) is represented by this increment factor. The resulting rainfall in each catchment was obtained by the multiplication of average rainfall in the catchment and the incremental factor. The incremental factor was specified before simulation so that it could generate the appropriate rainfall for simulation. For example, a factor value of 0.9 gives a 10% decrease in average rainfall and a factor value of 1.1 gives 10% increase in average rainfall.

Undertaking the water balance analysis for the reservoir

At the reservoir, the water balance was determined based on inflow and outflow as outlined in Equation 6.1:

$$\text{Storage}(t) = \int_{t_0}^{t_n} (\text{inflow}(t) - \text{outflow}(t))\,dt + \text{Storage}(t_0) \text{ ....} \textit{(Equation 6.1)}$$

Where Storage (t) = amount of storage at time t

Inflow (t) = inflow at time t

Outflow (t) = outflow at time t

t is any time between t_o and t_n ($t_o \leq t \leq t_n$)

Considering the fact that the main inflow is contributed by the streamflow and the outflow consists of evaporation losses from the reservoir surface and release to the downstream, storage at time (t) was expressed as Equation 6.2,

$$\text{Storage in reservoir}(t) = \int_{t_0}^{t_n} (\text{streamflow}(t) - \text{evapo. losses}(t) - \text{release to downstream}(t))\,dt$$
$$+ \text{ available storage}(t_0) \text{ ....} \textit{(Equation 6.2)}$$

Estimation of evaporation from a reservoir surface is a complex process. Pan evaporation and reservoir surface area can be used for estimating evaporation from lake surfaces using a suitable pan coefficient (Jensen 2010). The surface area of the reservoir does not remain constant when the storage level varies. It changes with the variation in storage level and it is difficult to obtain actual data of the surface area relative to storage level variation. Surface areas of all the reservoirs could be obtained from available data sources at full capacity level. For intermediate storage levels, interpolated values for surface area were determined between zero and the full capacity surface area as the surface area becomes zero for an imaginary zero storage level in the reservoir.

The main outflow processes from the reservoir and relationships are given in Figure 6.5. The arrows link the parameters to the main outflow processes.

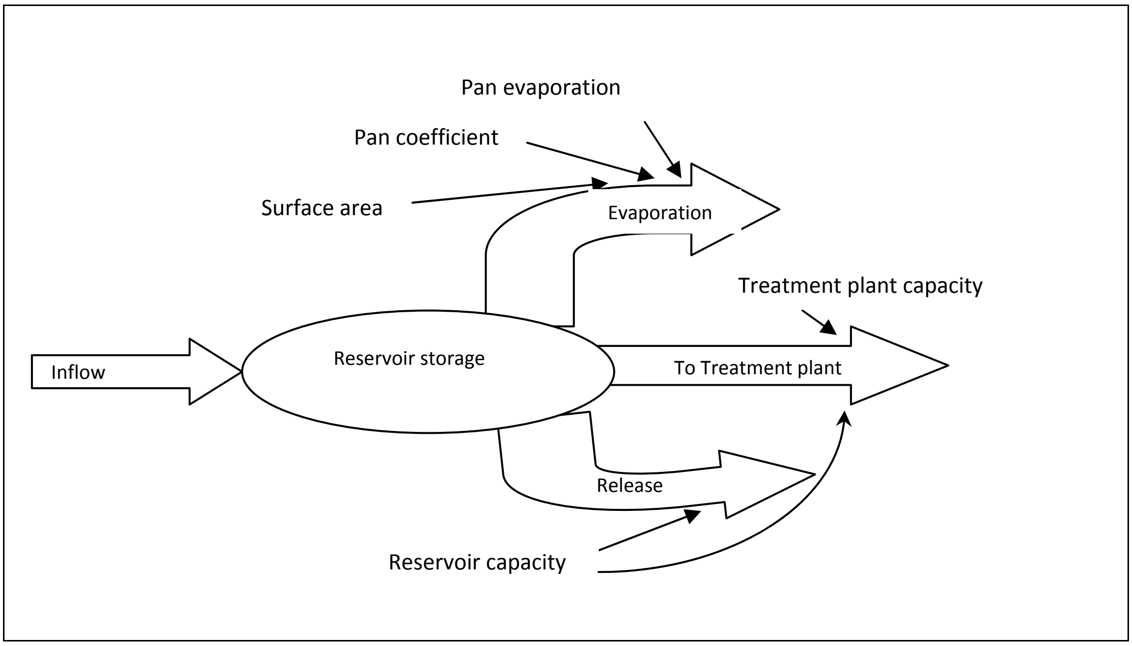
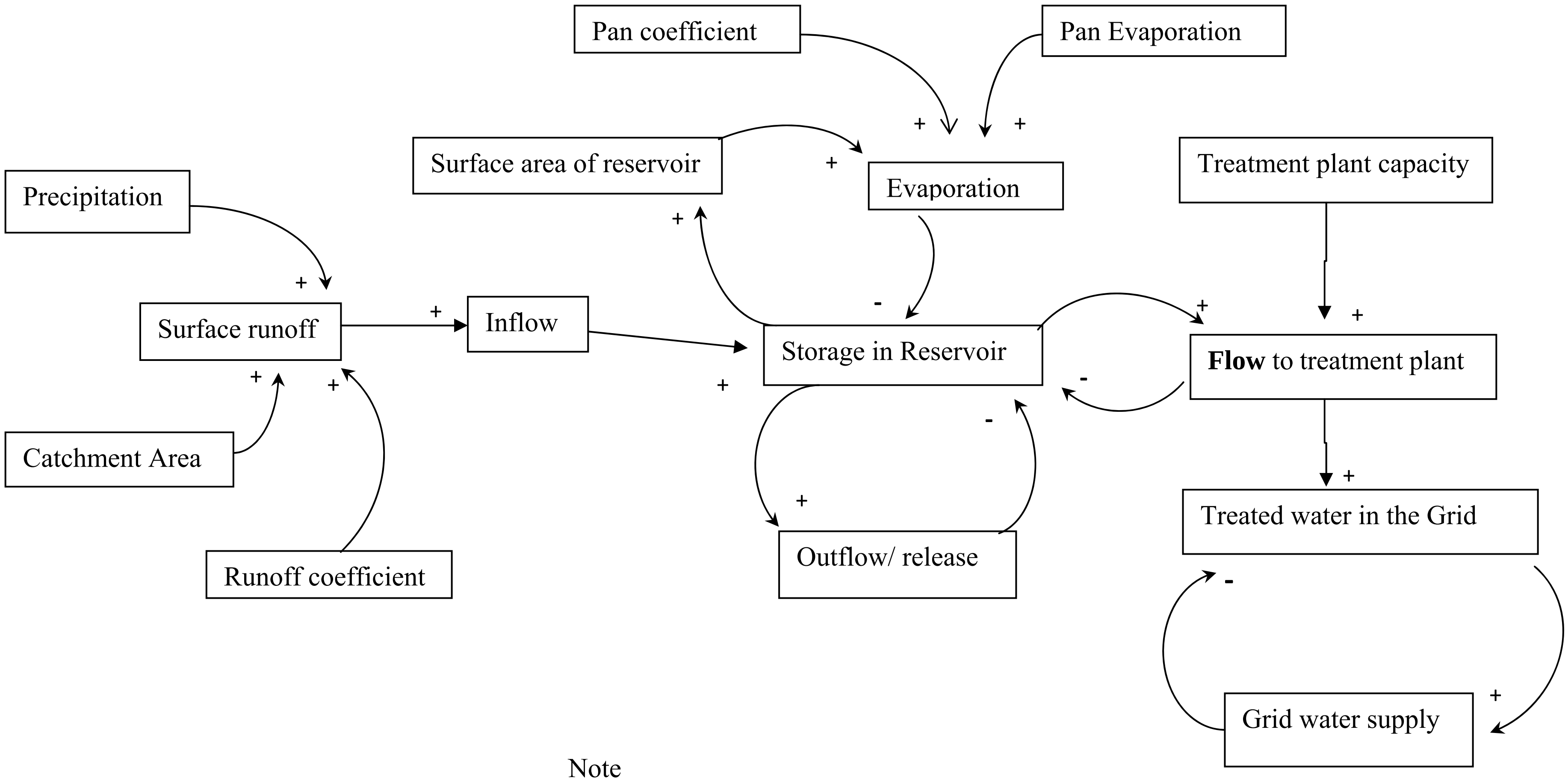


Figure 6.5 –The main outflow processes and the dependant parameters

Evaporation, release of excess water to the downstream and extractions by the treatment plant were considered as the main outflow processes. Pan evaporation, pan coefficient and surface area were taken into consideration to estimate the volume of evaporation. Therefore, the estimated volume of evaporation depends on these parameters, which were discussed in Section 6.3.2. Water extractions for treatment depend on the treatable capacity of the treatment plant and the capacity of the reservoir as discussed in Section 6.3.1. The excess quantity of water release depends on the reservoir capacity. Based on the above relationships, the CLD for a single catchment was developed and combination of CLDs for all the catchments formed the complete CLD for the entire Water Grid. CLD for a single catchment is shown in Figure 6.6.



Note

The arrows indicate that the two parameters /processes are related and the polarity indicates the type of connection (negative or positive)

Figure 6.6 – CLD for a single catchment

Based on the CLD, it was possible to estimate the behaviour of different variables of interest and the overall behaviour of the system. Development of the CLD completed the conceptualisation stage and was followed by the formulation stage, which improved the model up to the activation stage.

6.3.2 Formulation

The objective at this stage was to convert the conceptual SD model into an operable form. The method of activation was to develop a simulation model by creating a stock-and-flow diagram of the causal loop diagram. After developing the stock and flow diagram, it was necessary to input actual data which allowed simulation of the model. Model simulation activates the key function of the system, which is the flow of water from the catchment to the end users. From the simulation results, it was possible to observe the behaviour of the system in terms of output variations which could be produced in terms of graphs or tables. Since the model was based on system dynamics, the emphasis was on understanding trends and behaviour rather than values and numbers as pointed out by Madani and Marino (2009).

Depending on the intended purpose, two types of model simulations are common in practice. They are deterministic and stochastic model simulations. The SEQ Water Grid model included a mix of characteristics suited to both, deterministic as well as stochastic modelling. The differences between these two types of modelling and how they relate to the SEQ Water Grid model are discussed below.

Deterministic models produce a certain output with fixed input data. It gives the same results for different simulations unless the input data is changed. Hence, deterministic models are useful for special tasks provided that (sufficiently) unbiased results are produced from reliable input data (Gustafesson and Sternad 2013).

In contrast, stochastic model simulations give changed output for unique input for different model simulations due to the inclusion of random components in the modelling process. However, a single simulation gives only one possible result. Hence, multiple runs are used to estimate probability distributions. Sarkar (2002) noted that stochastic modelling is more relevant for analysis and optimisation of a specified system. Since the SEQ Water Grid model included input data in the form of probability distributions as well as numeric values, the model included a mix of characteristics of deterministic as well as stochastic modelling. The development of the SEQ Water Grid Model was carried out as a step-by-step process, which is detailed in the next section.

Development of the simulation model or the Stock and Flow Diagram

The STELLA software was used to develop the stock and flow diagram of the SEQ Water Grid model. The STELLA software is a system dynamics modelling tool implemented in object-oriented programming environment. It models systems using three simple entities. These are:

- Stocks - things that can accumulate;
- Flows - that flow into and out of the stocks;
- Converters and connectors - mathematical relations with stocks and flows.

STELLA has many inbuilt mathematical functions that can be easily used for simulations. For a dynamic model, it is necessary to execute a number of computations at a single time step. In STELLA, the process of carrying out these computations is automated, thus making model development fast. The output can be obtained, both in digital and graphical form. While the digital output can be used for further analysis, graphical output enables visualisation of the results. Other key features of STELLA were discussed in Section 4.4.

Figure 6.7 gives the Stock and Flow diagram based on the CLD given in Figure 6.6 for a single catchment and reservoir. The diagram indicates how the input parameters are related and how the flows are linked to the stocks. For development of the complete model, all the catchments of the SEQ Water Grid were combined.

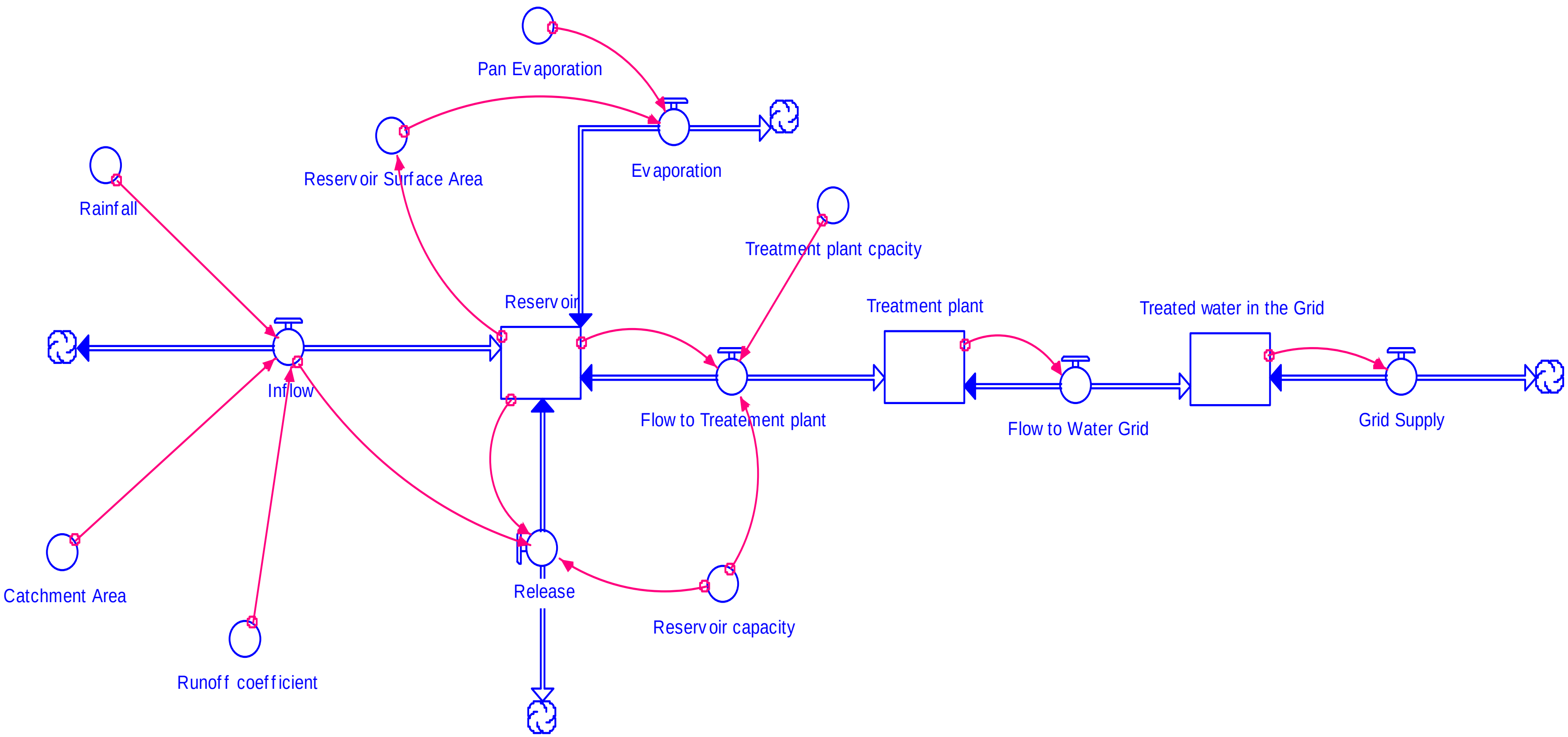


Figure 6.7- Stock- and- Flow diagram for a single catchment

After developing the SFD, the next step was to input actual data and undertake the simulations. Appropriate equations were employed to develop the relationships for data input where necessary. The equations considered as input relationships are discussed in the next section.

Input parameters and equations

The runoff volume generated from rainfall received by a catchment was approximated using Equation 6.3 (based on rational formula for runoff estimation):

$$Q = CIA \quad \text{..} \textit{(Equation 6.3)}$$

Where Q = Runoff volume

C = Runoff coefficient

I = Rainfall received

A = Catchment area

The overall catchment area data was obtained from the relevant water authority. For creating typical annual rainfall data, monthly rainfall data from 1997 to 2011 were considered.

In order to derive the runoff coefficients for each catchment, Equation 6.4 and Equation 6.5 were used. Equation 6.4 was based on the following fundamental relationship for quantifying rainfall excess (runoff) given by Wanielista *et al.* (1997):

$$R = C \times P \quad \text{..} \textit{(Equation 6.4)}$$

Where R = Rainfall excess

C= Runoff coefficient

P = volume of precipitation

In this equation, rainall excess (runoff) is expressed as a fraction of precipitation. Runoff coefficient (C) accounts for all losess. In order to obtain the volume of precipitation (P) in the catchment, rainfall depth was multiplied by the catchment area. Accordingly, volume of precipitation (P) in the catchment was obtained from:

$$P = A \times R_d \quad \text{..} \textit{(Equation 6.5)}$$

Where A = Catchment Area

R_d = Rainfall depth

Streamflow and rainfall data were used to derive the runoff coefficient for each catchment, considering that the rainfall excess was equal to the streamflow generated in the catchment. Streamflow data for the river upstream of the dam (obtained from Department of Environment and Resources Management) was plotted against data from the rainfall gauging station closest to the streamflow gauging station (obtained from Bureau of Meteorology or Department of Environment and Resources Management) for the same month. For example, for the monthly streamflow and rainfall data for the Hinze Dam catchment from January 2007 to January 2012, the scatter plot is shown in Figure 6.8. Other scatter plots are given in Appendix A. The gradient value of the best fit line was obtained as the runoff coefficient of that catchment and explanation for selecting a linear relationship is given below. The runoff coefficients were derived for each catchment.

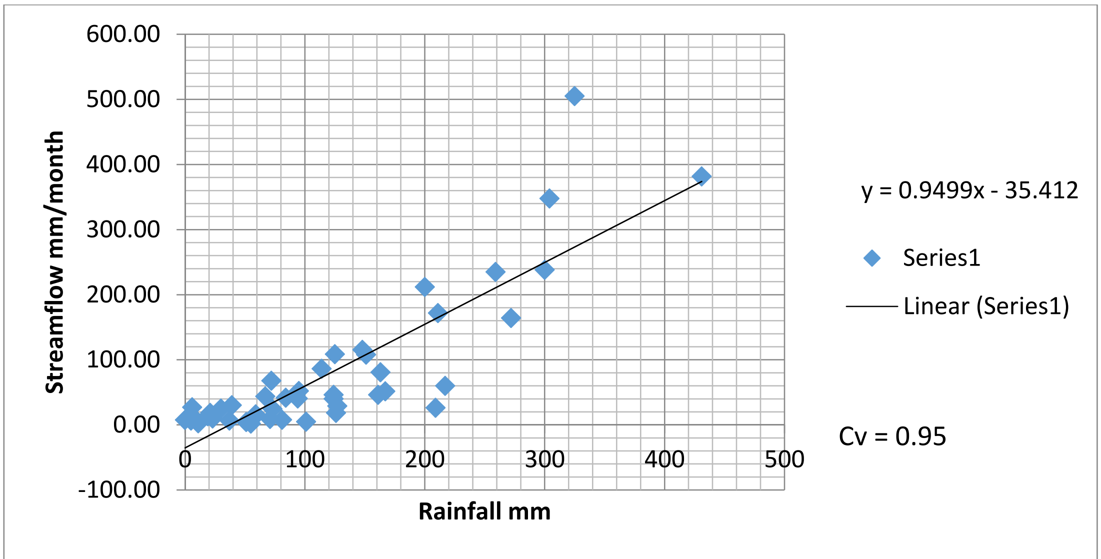


Figure 6.8 –Scatter plot for rainfall and streamflow for Hinze catchement

The runoff coefficient represents the fraction of rainfall converted to runoff. For this research study, a reasonable assessment of the runoff volumes can be obtained by using a runoff coefficient. It depends on a diverse range of factors as mentioned above. These factors vary depending on climate conditions. The relationship between rainfall and streamflow is not exactly a linear relationship. Therefore, the runoff coefficient of a catchment varies and is not a constant throughout the year. Furthermore, the relationship differs from catchment to catchment. However, to evaluate the exact relationship between these two parameters, long term data collection of rainfall and streamflow should be carried out simultaneously and evaluated for each catchment. However, due to the time constraint in this study for carrying out such data collection for each catchment, available historical rainfall and streamflow data were used for evaluating the runoff coefficient.

The water flowing into the rivers does not increase rapidly with the increase in rainfall. Whereas, when the rainfall is more than a certain volume, the flow in the rivers increase much faster with the increase in rainfall. Noguchi et al (2005) pointed out that streamflow increases proportionally after an initial rainfall of 30mm and this threshold can be higher in dry condtions. Therefore, for monthly rainfall less than 30mm, the runoff coefficient was considered as zero assuming no runoff generation occurs below this threshold value. For modeling, to avoid the complexity of changing nature of the runoff coefficient, the gradient of the best fit line from linear regression was used to derive the runoff coefficient for each catchment, although the rainfall-streamflow relationship is not linear. The derived 'C' values for each catchment/reservoir subsystem are given in Table 6.2. The Maroochy subsystem consists of Wappa and Cooloolabin reservoirs and the Gold Coast subsystem consists of Hinze and Little Nerang reservoirs. For each subsystem, one runoff coefficient value was used instead of considering different runoff coefficients within the same subsystem.

Table 6.2 –Runoff coefficients for each catchment

Catchment/reservour subsystems	Runoff coefficient (C) values.
Maroochy (Wappa)	0.704
Ewen Maddock	0.71
Lake Macdonald	0.74
Lake Kurwongbah	0.80
Maroon	0.20
Moogerah	0.02
Gold Coast (Hinze)	0.95
Leslie Harrison	0.15
Somerset	0.36
Wivenhoe	0.18
NorthPine	0.32
Baroon pocket	0.72

Water flow is the main process of a water supply system because it determines the functionality of the entire system. The runoff coefficient derived for each catchment was an important input parameter because it accounts for losses and determines the amount of rainfall volume transformed into a runoff volume. Therefore, the accuracy of model output mainly depends on the accuracy of the derived runoff coefficient values.

Accordingly, for the verification of the derived 'C' values, the actual storage data for each reservoir for each month (during the period 2008 to 2010) were compared with the simulated storage volumes using the derived 'C' values. The simulated values and the actual values showed a good match, indicating a reliable outcome. The comparison graphs are given in Appendix B.

The following relationship as given in Equation 6.6 was used for estimation of the evaporation volume. Kohler *et al.* (1955) and CSIRO (2008) recommend a value between 0.6-0.8 as a pan coefficient for estimating evaporation from lake surfaces. Accordingly 0.75 was assumed as the pan coefficient in this study.

$E_r = PE \times C_p \times SA_r$ ....*(Equation 6.6)*

Where E_r = Evaporation from reservoir

PE = Pan evaporation

C_p = Pan Coefficient

SA_r = surface area of the reservoir.

Input data applicable to the reservoirs, catchments and treatment plants are given in Table 6.3.

Table 6.3- Reservoir, catchment and treatment plant input data used in modelling

Reservoir	**Reservoir Capacity (ML)**	**Catchment area(km2)**	**Reservoir Surface Area (ha)**	**Treatment plant details**	**Treatment Plant capacity ML/month**
Baroon pocket	61,000	72	400	Landers Shute WTP (130ML/d) Maleny WTP (2.2ML/d)	4021
Ewen Maddock	16,587	21	370	E.M WTP (20ML/d)	608
Cooloolabin	13,800	8.1	220	Image Flat WTP (18 ML/d)	548
Wappa	4,694	69.7	75		
Lake Mac Donald	8,018	49	260	Noosa WTP(30ML/d)	913
Wivenhoe	1,165,238	7020	10,900	Mt Crosby East, west (916ML/d) Lowood WTP (20ML/d)	28470
Somerset	379,849	1340	4,210	Wood ford WTP (20ML/d) Esk WTP (0.8 ML/d) Somerset dam WTP(0.5ML/day)	648
North Pine	214,302	348	2,200	N.P WTP (220ML/d)	6692
Lake Kurwongbah	14,370	53	328	Petrie WTP (45ML/d)	1369
				Caboolture TP (14ML/d)	420
Leslie Harrison	24,868	87	479	Capalaba WTP (18ML/d)	548
Moogerah	83,765	228	827	Boonah Kalbar WTP (3.5ML/d)	107
Maroon	45,319	106	310	South Maclean WTP (11ML/d) Bearderst WTP (4.8ML/d) Kooralbyn WTP (1.9ML/d) Rathdowney WTP (0.4ML/d) Canungra WTP (0.6ML/d)	569
Little Nerang	6,705	35.2	49	Mudgeeraba WTP (100ML/d) Molendinar WTP (165ML/d)	8060
Hinze	310,730	207	1,500		

6.3.3 Input devices and in-built functions

The SEQ Water Grid model was required to perform mathematical and logical operations during simulations. STELLA software has a number of input devices and in-built mathematical and logical functions that facilitate the required operations.

The functions used for modelling the SEQ Water Grid model are discussed below. The SEQ Water Grid model was developed as a stochastic simulation model. Therefore, input rainfall data was considered as a normal distribution. The NORMAL function in the software was used to input logarithmic mean and standard deviation values of monthly rainfall for the five year period. The NORMAL function generates a normal distribution when the mean and standard deviation are inserted. However, as the input rainfall values were in logarithmic scale, the exponents of these values were required for simulation. Therefore, the EXP function was used to obtain exponents of the input values.

The logical functions - IF, THEN, ELSE, AND, OR, NOT - were used when conditional decisions were required. For example, *If* the storage level < 20% of capacity, flow to treatment plant was restricted to 0 *else* specified volume (depending on the treatment plant capacity). These functions give values based on whether the resulting expressions are TRUE or FALSE.

A graphical input device was used to input interpolated reservoir surface area data. Knowing the full storage surface areas of the reservoirs and considering zero surface areas when the reservoirs do not contain any water (an assumed situation), the intermediate values were given as a graph to select the appropriate surface areas for each interpolated point used for the simulation.

The evaluation was carried out for different storage conditions in the reservoirs. As there were number of reservoirs, changing the storage levels of each reservoir for each simulation was time consuming. To facilitate this evaluation, the knob device as a graphical user interface was used as a convenient way of changing the storage levels of reservoirs when required. The knob device allows changing the input value from 0% to 100% as required, by regulating the input value before running the simulation. The complete set of knob input devices for each reservoir is shown in Figure 6.9.

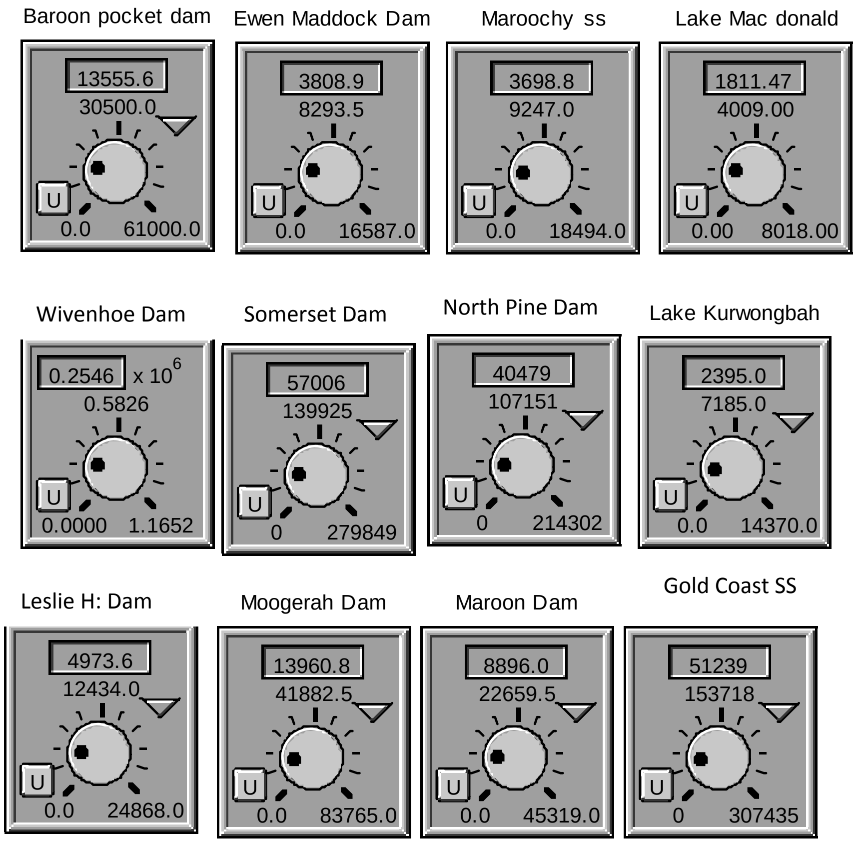


Figure 6.9 – Knob input device for easy regulation of reservoir storage levels

The numbers indicate the storage from 0% to 100%. For example, the full capacity of Baroon Pocket Dam is 61,000 ML. By turning the knob to the desirable position before the model run, the required storage level can be determined.

6.4 CONSTRAINTS ON MODELLING

The SEQ Water Grid is a water supply system with a very diverse array of component subsystems consisting of individual water supply systems. The general operations of the system are carried out under the guidelines provided in the South East Queensland System Operating Plan (Queensland Water Commission 2012). This operating plan includes operating rules which encompass management decisions that involve continuous monitoring. These decisions are sensitive to a given situation and hence cannot be generalised. Therefore, it was not possible to include such management interventions in the model.

For estimating the runoff coefficients for each catchment, rainfall and streamflow data were used. For accurate estimation of the runoff coefficient, rainfall and streamflow data needed to correlate. Rainfall and streamflow data obtained from the same monitoring location were not available for some catchments. Although data from the closest possible rainfall and streamflow gauging stations for the same time period were considered in the analysis undertaken, a margin of error was expected.

Runoff depends on factors such as rainfall intensity and antecedent dry days. Such information was not available for all of the historical rainfall data used in the study. Therefore, this information was not incorporated for deriving the runoff coefficients, resulting in a possible margin of error.

For evaluating the relationship (trend) between water quality degradation and the reduction in treatment potential in the treatment plant, detailed water quality data and data on the performance of the treatment plant is required. Such data is not readily available for any of the treatment plants in the SEQ Water Grid. Furthermore, undertaking an experimental analysis was not undertaken as this was outside the scope of this study. Therefore, the treatment reduction was assumed as a 10% decline for above-monthly-average rainfall events.

6.5 SUMMARY

As a part of this research, a case study was designed to apply the resilience evaluation framework to a real world system (the SEQ Water Grid). The water supply system was conceptualised as a meta-system with three nested subsystems. The three subsystems are the catchment/reservoir, the treatment plant and the distribution system. Considering these three nested subsystems as a single water supply system and evaluating the relevant relationships, the SEQ Water Grid model was developed using STELLA software. System dynamics was the modelling technique used in this study.

Suitable empirical equations were used and the boundary conditions were defined to develop relationships between input parameters at catchment scale in order to produce a causal loop diagram for a single catchment. The causal loop diagram for each catchment was converted into a stock and flow diagram and combined to develop the complete stock and flow diagram. The model was designed as a stochastic model to observe system behaviour under different rainfall scenarios, and evaluated against different population scenarios in order to understand the resilience characteristics of the overall system. Monitored data and derived parameters (based on actual data) for the SEQ Water Grid was used as input parameters.

The model was used for evaluating performance variations as a response to input variations. The system capabilities (particularly with respect to the selected resilience characteristics) could be evaluated by simulating the model under different scenarios. However, as this was not a hydraulic model and discrepancies were found in historical data, there were some limitations.

Chapter 7: Selection of Performance Indicators

7.1 BACKGROUND

System resilience is a concept that is not directly measurable. Hence, in order to evaluate the resilience of a system, a means of understanding systemic resilience is required. Accordingly, the development of a method to understand systemic resilience is important from a management perspective. Use of indicators is a widely accepted method in scientific analysis in many fields. However, it is important to select indicators that are specific and relevant to the intended purpose. Identifying suitable operational indicators was considered as part of the resilience assessment in this study.

A common usage of indicators is in the performance evaluation of systemic behaviour ranging from individual systems to organisations or different countries. However, indicators used for performance evaluation will vary depending on the nature of the performance being investigated. Therefore, selection of appropriate indicators is a complex procedure that needs careful attention in line with their intended purpose.

Chapter 5 of the thesis discussed the selected water supply system (SEQ Water Grid) and Chapter 6 outlined the modeling of the system in order to assess system behavior under different scenarios. This chapter is focused on selecting suitable indicators that can evaluate system behavior obtained from model simulations in order to assess systemic resilience of a water supply system.

7.2 PURPOSE OF USING INDICATORS IN THIS RESEARCH STUDY

Common purposes of using indicators can be identified as (NHS 2012):

1. Understanding how a system is performing and how it might be improved;
2. Performance monitoring;
3. Accountability and governance.

This research is focused on assessing resilience of a water supply system to pressures exerted by climate change and population growth impacts. Hence, as noted in the first point above, a thorough understanding of how the system works under pressure was an important reason of using indicators in this study, which is in line with the resilience assessment process. This was achieved by evaluating performance against the selected indicators.

Unfortunately, only limited attention has been given in the past towards identifying suitable performance indicators in the context of resilience assessment of a water supply system. This is a complex procedure, which requires the careful evaluation of relationships in a water supply system and the parameters that explain the output variations under specific pressures. The discussion below provides an approach for identifying suitable performance indicators for evaluating the resilience of a water supply system with specific pressures in relation to climate change and population growth.

7.3 AN APPROACH FOR IDENTIFYING SUITABLE INDICATORS OF RESILIENCE FOR AN INFRASTRUCTURE SYSTEM

Recognition of issues related to required information, noted as 'problem identification' by Winograd *et al.* (1999), was an initial and important step for selecting indicators. Defining clear objectives for selecting indicators is equally important. Selection of indicators to suit well-formulated project objectives is a requisite, so that resilience characteristics can be represented in the important stages of the system operation.

The primary resilience characteristics intended to be evaluated in this study were the ability of the system to withstand pressure and the ability to recover. The objective of selecting indicators was to assess these characteristics against selected indicators in order to understand systemic resilience.

Joshi and Gupta (2010) highlighted the importance of setting objectives to evaluate different performance measures. They evaluated performance of a multi-purpose multi-reservoir system with five objectives and formulated indicators for each of the objectives. They noted the essential need for setting-up an objective as a primary requirement in the process of identifying indicators and illustrated as given in Table 7.1.

Table 7.1 – Indicators for measuring different aspects of a project for different objectives (adapted from Joshi and Gupta 2010)

Objective	**Performance measure/ formulated indicator**
Meeting volume reliability of water demand for industrial, domestic and irrigation use	Water availability indicator Volume Reliability Index (*VRI*)
Meeting time reliability of water demand for industrial, domestic and irrigation use	Water reliability indicator Time Reliability Index (*TRI*)
Meeting hydropower production targets of the system	Hydropower potential indicator Hydropower Production Index (*HPI*)
Earning revenues from the system to meet operation and maintenance cost of the project	Economic benefits indicator Economic Benefits Index (*ECBI*)
Reducing loss of water and energy through spills in the system by preventing spill events	Spill events indicator Spill Prevention Index (*SPPI*)

The indicators noted in Table 7.1 were based on a set of objectives which aimed to evaluate different aspects of the overall system performance. Separating different types of performance measures as shown above, enables procurement of information leading to the evaluation of the different aspects of performance.

In order to understand how climate change and population growth pressures influence the operation of a water supply system, it is useful to consider the influence on different subsystems within the water supply system. As discussed in Chapter 1, the meta-system (that represents a complete water supply system) consists of three main subsystems; water catchment/reservoir (first level), treatment plant and relevant infrastructure (second level) and the end users (third level). The inflow to the system is a function mainly associated with the first level; catchment and reservoir. The impact of pressure is reflected by the output variations at the third level. Systemic resilience determines the degree of service reduction due to the pressure of low rainfall. Therefore, establishment of a relationship between the pressure at the first level and the service delivery at the third level is required for identifying the parameters that explain the pressure - service delivery relationship.

Water inflow is influenced by variations in rainfall parameters. In order to consider the variation of rainfall parameters as the main pressure, a reference rainfall year has to be defined as the 'design pressure'. However, the average monthly rainfall is not the same for every month of the year. Therefore, it is not possible to consider a single rainfall value as the reference. The reference (design) pressure is a rainfall pattern for an average year, which consists of different values of average monthly rainfall for different months of the year.

The reduction in rainfall (increase of pressure) means reduction in rainfall from each reference month. The design (reference) pressure is not a single rainfall value, but a pattern of rainfall values extended over a year. Therefore, further considerations are required for incorporating these pressures.

Analysis of pressure – service delivery relationship is an important step for identifying suitable indicators in the context of systemic resilience as defined in this study. Figure 7.1 illustrates the relationships between the pressures and service delivery.

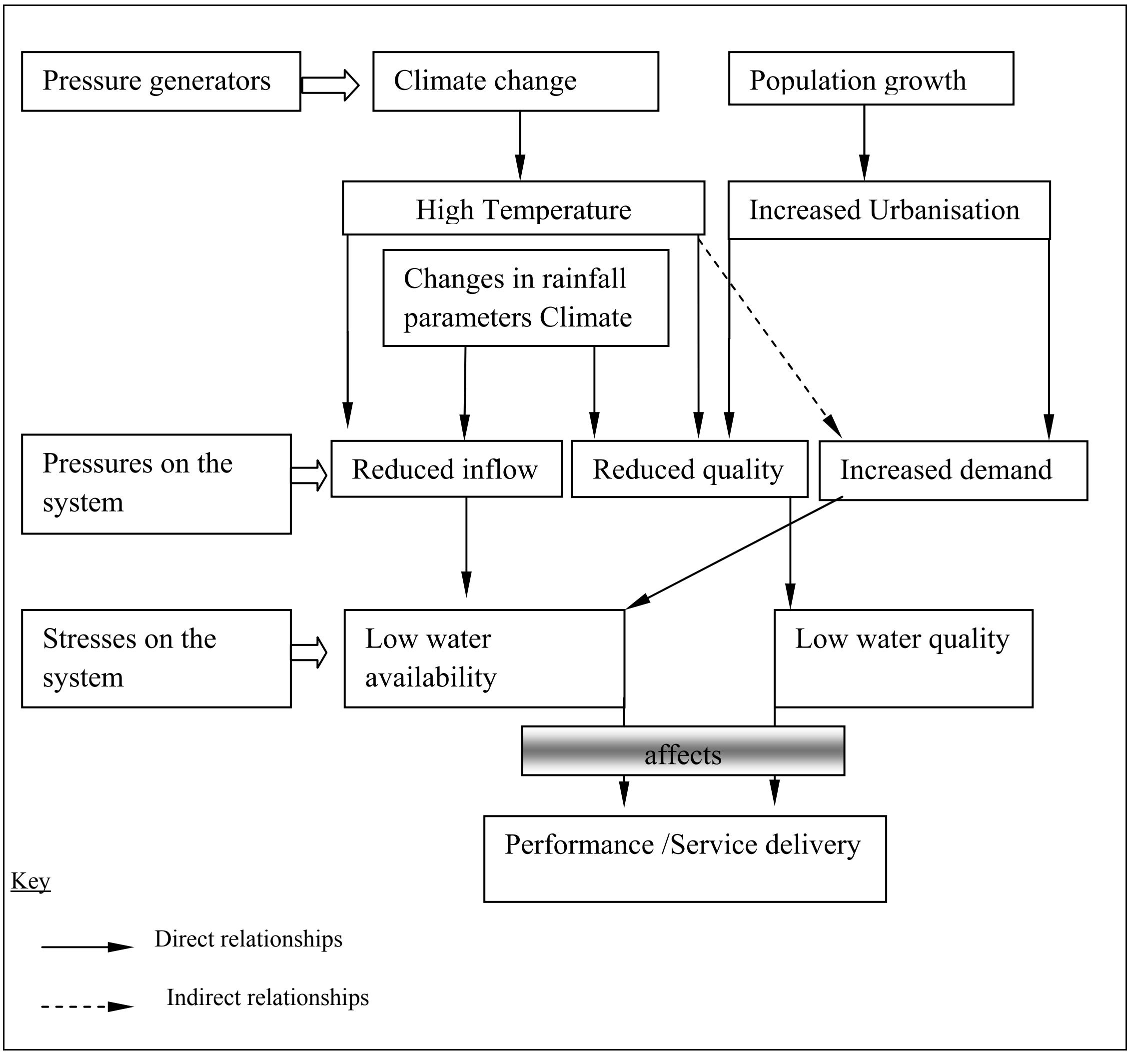


Figure 7.1- Relationships between the pressures and the service delivery

The pressure-service-delivery relationships help to develop a criterion to assess if a water supply system is resilient. These relationships were developed based on the understanding gained from past research studies and published literature.

High temperature, changes in rainfall characteristics and increased urbanization, as consequences of climate change and population growth, apply pressures on a water supply system in the form of reduced inflow and reduced water quality (Figure 7.1), primarily at the first level of the meta-system. However, the increase in demand due to population growth applies pressure through to the third level. A detailed discussion on how climate change and population growth influence water inflow and quality is provided in Chapter 2. Relevant behaviour patterns of climate change and population growth are discussed below.

The main consequences of climate change in the context of this project are the changes in temperature and rainfall characteristics. Similarly, demand variation is the main consequence of population increase. Therefore, it is important to understand the pattern of occurrence of these pressures. Figure 7.2 illustrates the rainfall, temperature and population trends for Queensland/Brisbane over the period of 2001 -2011.

The comparison of Figures 7.2a, 7.2b and 7.3c shows that rainfall has a highly fluctuating behaviour compared to the other factors. Temperature change is very minor and population growth is very regular. Therefore, population growth rate can be assumed as a very smooth variation. Per capita water consumption rate will not fluctuate significantly. Therefore, other than for rainfall, it can be assumed that changes to other parameters can be predicted with reasonable accuracy. Provisions can be incorporated in the system designs to facilitate predictable variations. However, in case of rainfall there can be sudden or unexpected low rainfall occurrences as in year 2002 and 2005 (Figure 7.2a). In such circumstances, the pressure acting on the system fluctuates within a short time period. The system responds accordingly by demonstrating a low level of service delivery.

The pressures mentioned above, create 'stresses' on the system. Stresses are the conditions that compel the system to define (or reduce) the final service level. The stresses on the system are '*low water availability in the reservoir'* and '*low quality of available water*'. Level of final service delivery depends on the amount of stresses on the system. A resilient system delivers a relatively higher level of service even under highly stressful conditions.

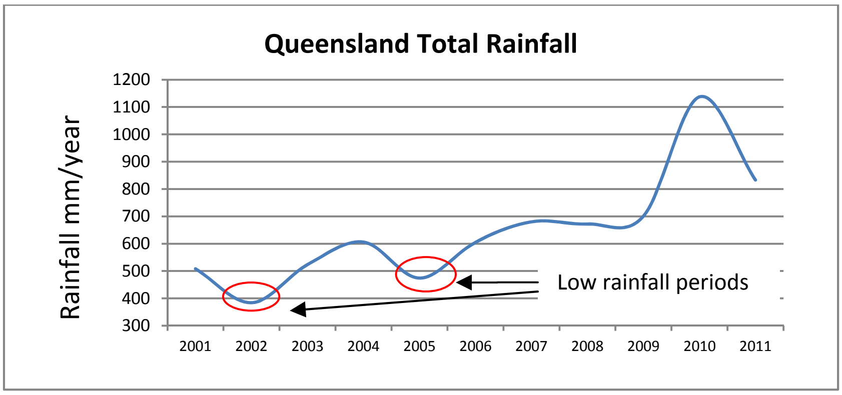


Figure 7.2 (a) Queensland annual rainfall totals (data from BOM)

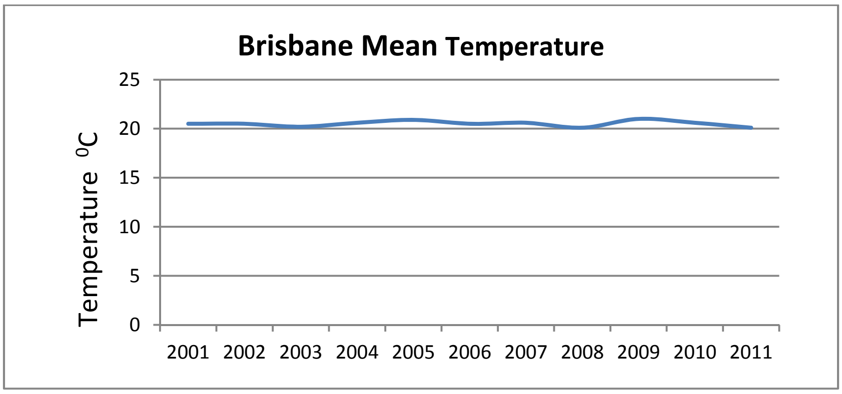


Figure 7.2 (b) Brisbane Mean Temperature (data from BOM)

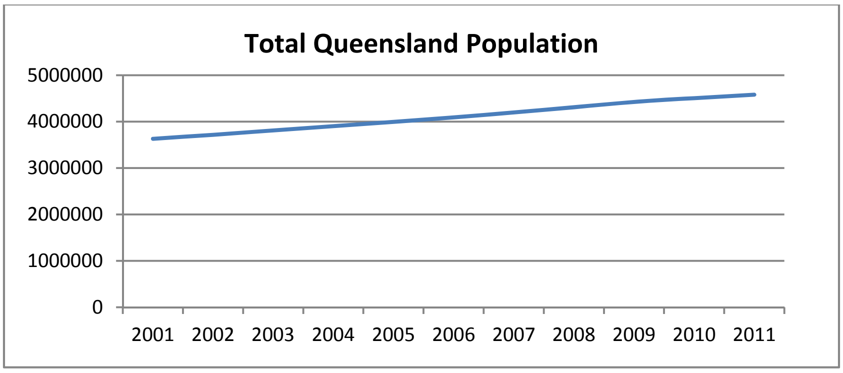


Figure 7.2 (c) Queensland Population (data from ABS)

Figure 7.2 - Rainfall, temperature and population trends for Queensland/Brisbane over the period of 2001 -2011

Therefore, resilience as a function of service delivery can be expressed as;

$$R_s = f\,(S_d, a), \text{.....................................} \text{ (Equation 7.1)}$$

where R_s - resilience of the system

S_d - service delivery

a - other variables that influence resilience of the system

In deriving this equation, the following considerations were taken into account,

- The entire meta-system was considered.
- Service delivery is the final output that the system delivers to the end users.
- Level of service delivery is measured with respect to the maximum supply capacity of the system.

Disaggregating Equation 7.1 further down to the second degree level, service delivery and stresses can be defined as:

$$S_d = f\,(S_r, b), \text{.................................} \text{ (Equation 7.2)}$$

where S_r - stresses on the system

b- other variables that influence service delivery

As stresses on the system are created by pressures, a relationship can be expressed as:

$$S_r = f\,(P_r, c), \text{……………………} \text{ (Equation 7.3)}$$

where P_r – pressures acting on the system

C – other variables that influence stresses on the system

Considering the variables that contribute to create stress on the system, a relationship can be developed by further disaggregating Equation 7.3, as given in Equation 7.4. Inadequate inflow or higher demand can result in *low water availability*. Low quality of inflow water and degradation of reservoir water quality contribute to *low quality of available water*.

The third degree relationship, similar to the one introduced by Barnes *et al.* (2012), can be defined as:

$$Sr = f\,(\sum I_f, Q_{in}, Q_s, D_m, d), \text{............. (Equation 7.4)}$$

where I_f - inflow to the reservoir

Q_{in} - quality of inflow water

Q_s - quality of water in the reservoir

D_m - demand

d - other variables

In deriving this equation, following considerations were taken into account:

- I_f - Includes all inflow (surface runoff (I_s) + ground water flow (I_g) +others (I_o)). Therefore, the next degree of relationship can be written as $I_f = f$ (Is, I_g, I_o).
- D_m - is the demand corresponding to the per capita consumption rate multiplied by system population. System population is the maximum population that the system is capable of supplying, subject to the lowest maximum capacity of the subsystem in the meta-system.

The above relationships show the interdependencies of different attributes.

Based on the above relationships, the following diagram shown in Figure 7.3 illustrates links to identify a set of parameters that can be used to develop indicators to assess resilience of a water supply system.

As shown in Equation 7.1 and Figure 7.3, resilience is a function of service delivery. Therefore, in a resilience assessment key considerations are the ability of the system to deliver adequate services and the maximum pressure exerted on the system under which a system operates because a resilient system should be able to supply adequate quantity of water of specified quality under pressure. Accordingly, the criterion that a resilient water supply system should satisfy have been defined as '*adequate supply to meet service standards of water, under pressure*' (see Figure 7.3). In order to satisfy this criterion, successful activation of the entire meta-system is required. The selected pressures mainly apply through the first and third levels as discussed in

Section 7.3. The behaviour of the system in terms of failure or non-failure and compatibility to specified water quality is reflected at the third level. The management strategies are essentially focused on these levels where the pressures apply. Indicators should provide information for developing appropriate management strategies.

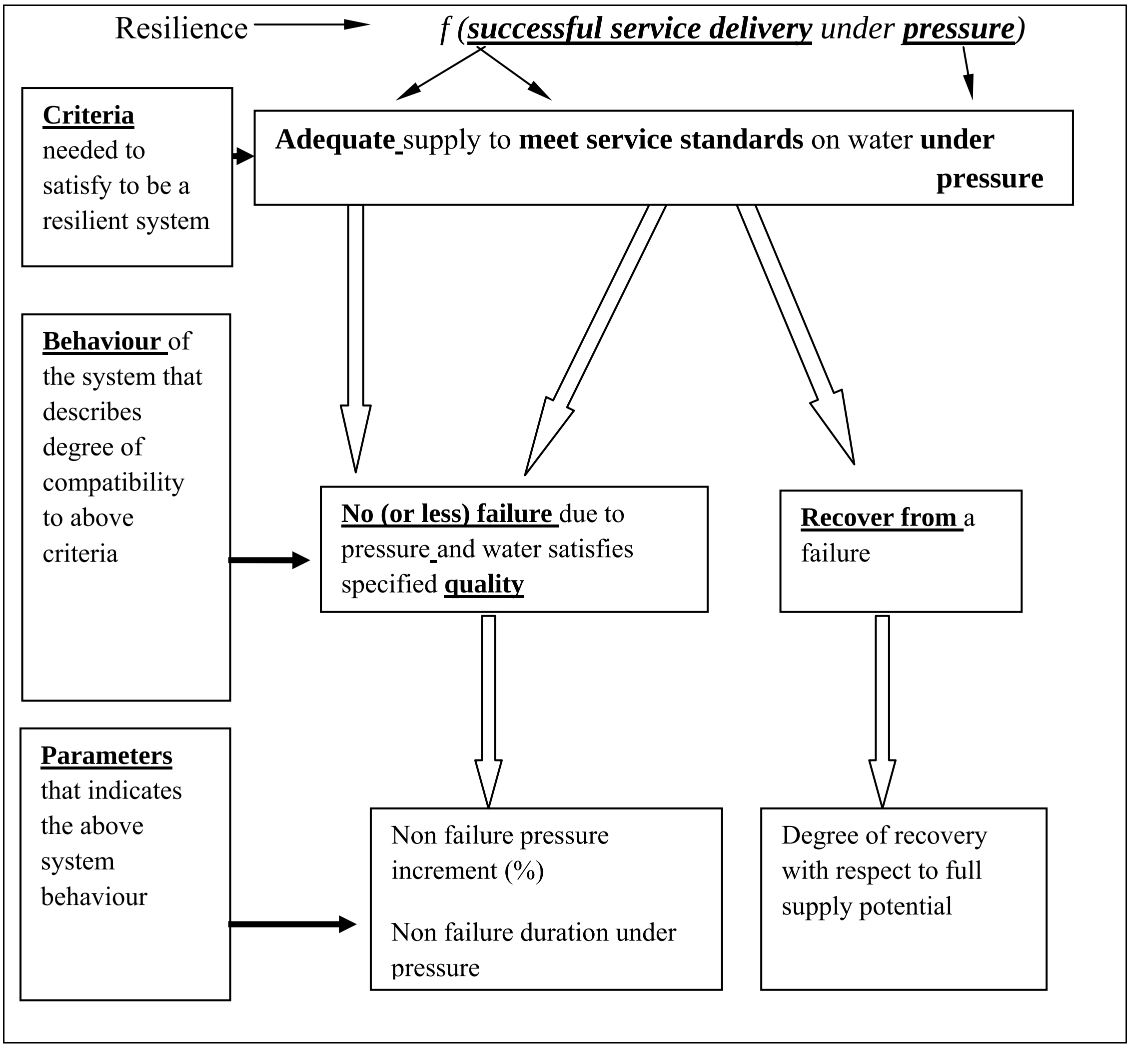


Figure 7.3 – Links to identify resilience indicator parameters

Accordingly, the indicators should incorporate the behaviour and the level of pressure in order to understand systemic resilience. Based on the approach discussed above, the fundamental requirements identified for developing indicators for evaluating resilience of a water supply system, considering rainfall variation as the main pressure are given below.

- Non-failure pressure increment percentage
- Non -failure duration under pressure
- Degree of recovery with respect to full supply potential.

Further explanation of these parameters and indicators are discussed below based on each set of parameters proposed by defining specific conditions.

7.3.1 Non-failure pressure increment percentage

The parameters included in this expression explain two considerations. They are the status of the system in terms of surrogate measure (zero probability of failure) and level of pressure acting on the first level of the system. Therefore, it links the pressure and the level of service delivery. High percentage increment of pressure (without failure), indicates high ability to absorb pressure. The 'pressure increment' refers to the increment above the reference (average) level.

For using this indicator a further important consideration should be taken into account. That is the level of storage, as failure is influenced by the available storage. High storage might allow greater rainfall reduction before reaching the failure threshold.

For assessing the resilience of a water supply system to climate change, with rainfall reduction as the main pressure, an indicator can be defined as,

'Non-failure rainfall reduction percentage (for defined storage capacity)'

For example, the above indicator can be termed for 50% storage as '*Non failure rainfall reduction percentage for 50% of full storage capacity*'. Accordingly, different storage scenarios should be defined in the assessment. The information reveals the ability of the system to withstand low rainfall pressure relevant to the defined storage level.

7.3.2 Non-failure duration under pressure

Non-failure duration under pressure provides information about the system capability to operate without failure when subjected to pressure. Non-failure status of the system for a longer duration under pressure indicates high resilience status of the system. However, it is necessary to define the level of pressure as well as the storage conditions to understand the resilience characteristics of the system. Therefore, based on non-failure duration under pressure, indicators can be developed to evaluate resilience of the system by identifying specific system behavior parameters, which is discussed in Section 7.4.

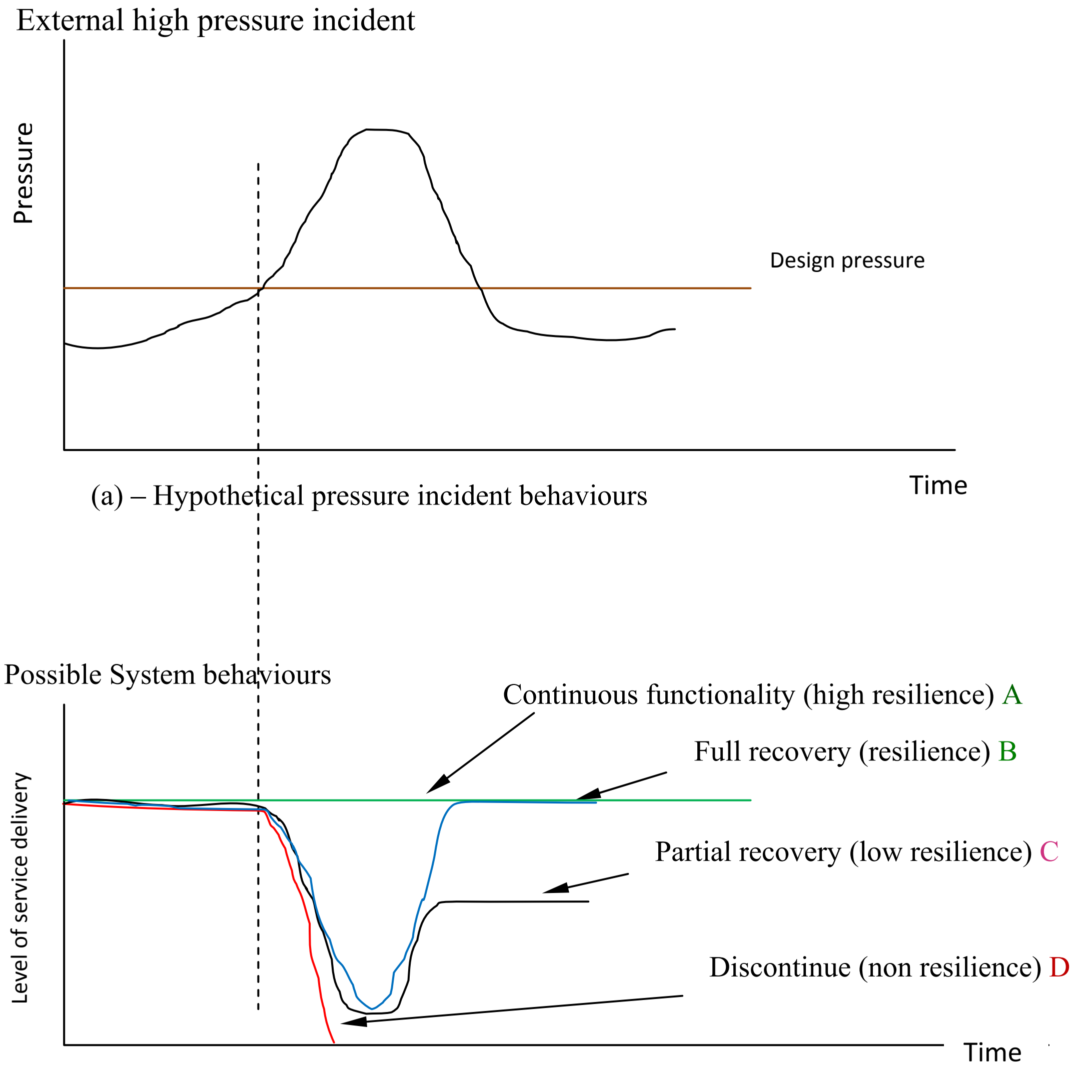
7.3.3 Degree of recovery with respect to full supply potential

The degree of recovery of the system can be identified by the output volume of potable quality water after recovery, compared to the full supply potential. High degree of recovery indicates high resilience of the system. By considering the parameters that indicate output variations, indicators can be developed to identify systemic resilience which is discussed in Section 7.4.

7.4 INDICATORS BASED ON SYSTEM SPECIFIC PARAMETERS

Further evaluation of system behaviour under pressure allows development of specific indicators that can be used to assess systemic resilience. Hence, it is necessary to explain how a system behaves during pressure situations in order to select parameters for developing indicators. However, the actual behaviour of a system can only be evaluated by modelling the system and simulating the system under desired scenarios. Initially, a typical situation was considered for identifying possible parameters that can be used for developing suitable indicators. Then the evaluation was extended to a water supply system operating under selected pressures of climate change and population growth. Figure 7.4 illustrates a typical external high pressure incident and possible responses for that pressure incident.

The Figure 7.4b shows possible system behaviours due to an external high-pressure incident corresponding to Figure 7.4a. Generally, when the pressure exceeds the limit that the system is designed for, decline in service is expected. The service may be either completely discontinued (scenario D) or partially recovered (scenario C) or fully recovered (scenario B). The most desirable behaviour is the undisturbed service provision as shown in scenario A, which is the most resilient behaviour. The ‘zero effect’ can be explained as a system’s ability to withstand pressure. Under scenario B and C, the system is affected by the pressure, but has the ability to recover fully or partially.



(a) – Hypothetical pressure incident behaviours

(b)- Possible system behaviours corresponding to the pressure incident illustrated in (a)

Figure 7.4- Possible system behaviour under external high pressure incident

Behaviour of a system in terms of service delivery can be further illustrated by plotting the level of service delivery as the dependent variable of pressure, as shown in Figure 7.5.

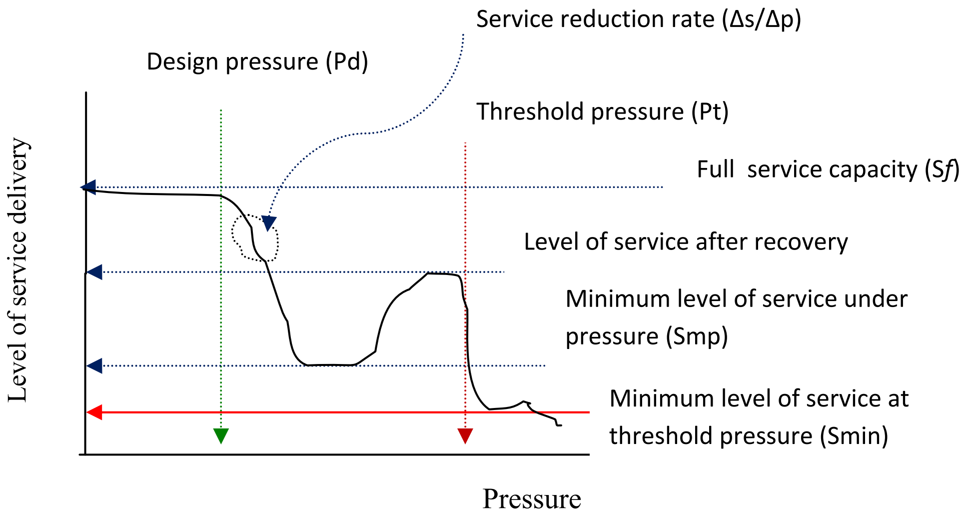


Figure 7.5 – Illustration of indicator parameters for a partially recoverable system

Generally, systems are allocated with sufficient resources to operate under foreseeable disturbances. Therefore, a system is expected to operate without failure up to that level of pressure, which is defined here as the *design pressure* limit. Further increase in pressure beyond the design pressure limit leads the system to reduce the level of service delivery. However, the system may recover (increased level of service delivery) to reach the original level of service or a lower level than the original level. After a certain pressure limit, the system may not be able to deliver a successful level of service any further (system failure). That level of pressure, when system failure occurs, is defined here as the *threshold pressure limit*. For a generic system with measurable service delivery, the parameters given in Figure 7.5 can be used for developing indicators to quantify the degree of systemic resilience.

For the assessment to be of value, the level of resilience should be related to thresholds that express the critical conditions of the system. For example, a large water supply system might reduce its supply potential by 90%, due to low rainfall, and operate at a 10% capacity level. Unless this 10% supply level is insufficient to satisfy a considerable percentage of the demand, there is no significant impact on the consumers. In this case, defining the system as a low resilience system because of low supply does not make any useful contribution from a management perspective since critical management decisions should not be involved, as the situation is not critical. On the other hand, defining such a system as a high resilient system is questionable as the service potential drops by 90% during low rainfall conditions, indicating low ability to withstand the pressure of low rainfall. Therefore, the parameters considered for developing indicators should be related to the failure threshold. The proposed indicators of resilience and their limitations are discussed below.

***A: Design pressure to Threshold pressure ratio* (R_{pp})**

$$\text{Ratio } (R_{pp}) = \frac{Pt - Pd}{Pd},$$

where P_t- threshold pressure for the system

P_d – design pressure

The 'threshold pressure' and the 'design pressure' (as defined) are system characteristics. Hence, this ratio quantifies the excess pressure beyond the design limit that the system is capable of absorbing in a crisis situation before an initiation of loss of service might be expected. For example, a value of 2 indicates that in a sudden high pressure situation, the system is capable of maintaining functionality up to two-fold of its design pressure. When applying this indicator to a water supply system to assess resilience to pressure due to low rainfall, the design pressure and the threshold pressure should be identified clearly because these pressures, when considering rainfall, are patterns of rainfall distribution instead of a single value. The term (P_t- P_d) can be considered as the reduced percentage of rainfall from the average to reach the threshold limit.

***B: Service reduction ratio* (R_{ss})**

$$\text{Ratio } (R_{ss}) = \frac{Smin}{Sf},$$

where S_{min} - minimum level of service at threshold pressure

S_f - full service capacity

This ratio indicates how much service reduction takes place between the full supply level and the threshold pressure supply level. S_{min} becomes 0 if the system completely stops functioning at the threshold pressure. However, depending on the definition of failure criterion, the system may not stop completely, although it may fail to supply a sufficient level of service. Accordingly, the ratio value (R_{ss}) of zero indicates complete stoppage of the system. A value close to unity indicates a low reduction of services, denoting a highly resilient system.

***C: Service reduction rate* (R_{sp})**

$$\text{Ratio } (R_{sp}) = \frac{(Sf - Smin)/Sf}{(Pt - Pd)/Pd},$$

where S_f – full service capacity

S_{min} – minimum level of service at threshold pressure

P_t – threshold pressure for the system

P_d – design pressure

This indicator quantifies the rate of service reduction with reference to the pressure increment. Higher rate of service reduction means low resilience as it shows low ability to absorb pressure (high sensitivity to adverse pressure). A highly resilient system may indicate low gradient and a low resilient system may demonstrate a steep gradient as illustrated in Figure 7.6.

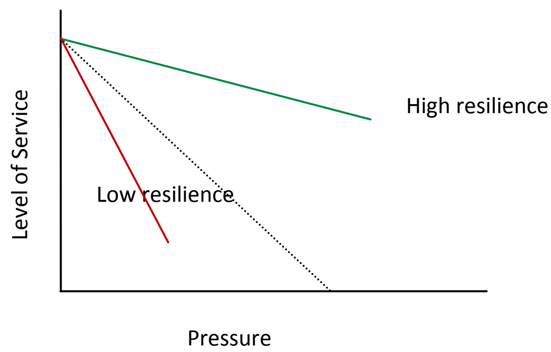


Figure 7.6 – Genaralised service reduction rates to pressure increase

In order to use this indicator for a water supply system to evaluate resilience to low rainfall conditions, the term (P_t- P_d) can be considered as the reduced percentage of rainfall from the average to reach the threshold limit similar to the ratio (R_{pp}).

D: Non failure ratio **(R_{nf})**

$$\text{Ratio } (R_{nf}) = \frac{\mathbf{Tnf}}{\boldsymbol{Tt}},$$

where T_{nf} –non failure duration

T_t – total observed duration

This indicator explains the length of non-failure duration under a defined level of pressure. When using this indicator, the level of pressure needs to be mentioned. Ratio value (R_{nf}) of unity or close to unity indicates no failure duration or low failure duration, demonstrating high resilience as the system indicates relatively high ability to withstand under that specified pressure.The range of Rnf lies between 0 and 1.

E: Recovery ratio **(R_{rr})**

$$\text{Ratio } (R_{rr}) = \frac{\boldsymbol{Sr}}{\boldsymbol{Sf}},$$

where S_r – level of service after recovery

S_f– full service capacity

This ratio indicates the degree of recovery (full or partial). Ratio value (R_{rr}) of unity indicates full recovery. A fully recoverable system can be considered as a resilient system depending on the time of recovery. The range of R_{rr} lies between 0 and 1.This indictor is useful only if the system recovers. It shows the ability to recover after service reduction.

The above indicators can be used for a generic system in which service delivery is sensitive to pressures acting on the system (as in Figure 7.5). The way of applying pressure on the system differs depending on the type of pressure. For example, the magnitude of the pressure may have regular increasing or decreasing behaviour. Irregular fluctuations of pressure can create more complex situations. Rainfall has irregular fluctuation patterns. Depending on the pressure variation patterns, restrictions may apply to some of the above indicators.

7.5 CHARACTERISTICS OF SELECTED INDICATORS

The proposed set of project level quantitative performance evaluation indicators contains the following characteristics, which are necessary characteristics of good indicators as noted by Winograd *et al.* (1999) and Dimic (2012):

- ***Direct relevance to project objectives*** - The indicators must be closely linked to the objectives. The selected indicators provide information about system behaviour under the pressure of rainfall variation. Evaluation of this information is directly relevant to resilience assessment of the system.
- ***Limitation in number*** - A small set of well-chosen indicators tends to be the most effective. The number of indicators selected in this study was six.
- ***Clarity in design*** - It is important that the indicators are defined clearly in order to avoid confusion. All terms relevant to selected indicators are explained clearly.
- ***Importance*** - The indicator must be relevant to similar systems and must relate specifically to the objective in question. The proposed indicators can be used in similar infrastructure systems with similar pressures acting on them.
- ***Scientific acceptability*** - The measure must be reliable and valid. Reliable means the indicator must give the same results in repeated measures and valid means it must measure what is intended to be measured.
- ***Feasibility*** - Data for indicators must be feasible to be obtained. Data for proposed indicators can be obtained from model simulation as designed in this study.
- ***Usability*** - The results of any measures must be understood by the intended audience. Measures that are difficult to understand will not be translated to meaningful improvement. The proposed indicators should be easy to understand.

7.6 SUMMARY

Indicators are used in many disciplines at different levels, and they can range from project level to global level. Therefore, indicators can be used for different purposes. However, the main objective of using indicators is to obtain information to aid in decision making. Quantitative as well as qualitative information can be obtained by a well-defined set of indicators. The process of indicator selection needs careful attention for defining the purpose of the required indicators. Good indicators need to satisfy certain criteria.

Relationships were evaluated carefully for selecting suitable indicators for the research study and the selection of indicators was based on these relationships. The storage and pressure conditions were also needed to be incorporated into the indicators. A set of project level, quantitative, performance evaluation indicators was selected for evaluating the resilience of a water supply system. The aim was to use the selected indicators for evaluating system behavior under different (pressure and storage) conditions in order to assess system's ability to perform under pressure. As the system capability to perform under pressure represents systemic resilience, the selected indicators could be used as a tool for assessing the resilience of a water supply system.

Chapter 8: System Behaviour and Uncertainty Assessment

8.1 BACKGROUND

A comprehensive evaluation of system behaviour is critical, as a system can demonstrate a range of outputs under varied conditions and scenarios (Barlas 2013). The performance parameters of a water supply system (WSS) are generally designed to match historical climatic data relevant to the particular region where the system is located. However, the system performance may not meet the expected requirements due to uncertainties impacting on system behaviour. Performance uncertainties in a water supply system can arise due to a range of reasons such as variations in climate conditions or changes intrinsic to the system itself. Past weather patterns including occurrences of droughts may not necessarily provide a reliable guide to predict future climate conditions due to factors such as climate change. Global temperature increase is a primary consequence of climate change. As global temperature rises, evaporation rates are expected to increase (Bates *et al.* 2008), with resultant impacts on water flows. This scenario influences propensities for drought in terms of both frequency (including longevity) and severity (Key and Davies 2008).

Evaluation of modelled system behaviour, including variations in output due to different disturbance/pressure scenarios relevant to an existing system, is a complex process. Long term monitoring and data collection specific to different disturbances/pressure events are required for this purpose. In situations where uncertainty is involved in selected pressures, such as in the case of climate change, the evaluation procedure can become even more complex.

This chapter is focused on evaluating the behaviour of a modelled water supply system considering the uncertainty and potential climate change impacts on the system. Behaviour of the modelled water supply system, the SEQ Water Grid, was simulated under different water availability scenarios in order to evaluate the potential pressure conditions due to climate change.

8.2. EVALUATION OF SYSTEM BEHAVIOUR

The most common behaviour patterns of dynamic systems are in the form of constant, growth, decline, growth-then-decline, decline-then-growth, and oscillatory behaviours (Barlas 2013) as illustrated in Figure 8.1.

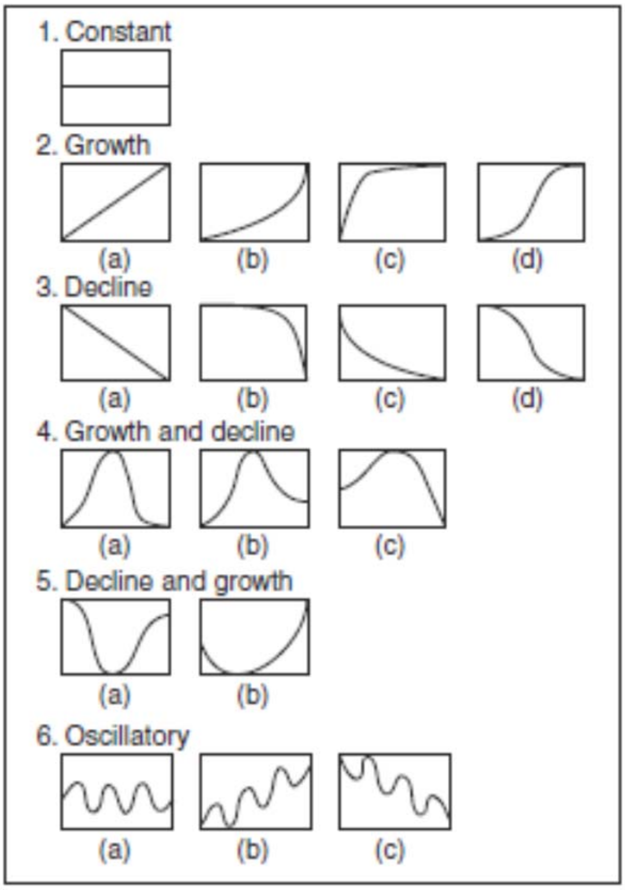


Figure 8.1 –Categories of basic dynamic behaviour patterns (Barlas 2002)

Service decline is expected under pressure situations in normal operating conditions. However, a resilient system is expected to show the least tendency to move to failure state under pressure. In other words, this characteristic may be highlighted as the ability to withstand the pressures being applied on the system. The constant behaviour (under pressure), as indicated in category 1 in Figure 8.1 can be an illustration of the behaviour of resistance to change. In a situation where the system output has declined, a measure of the ability to recover after a disturbance is a key resilience indicator. This suggests that depending on the degree of systemic resilience, the system might show decline-then-growth or oscillatory responses under pressure scenarios. In Figure 8.1, such behaviours are indicated in category 5a, 5b, 6a and 6b respectively. In contrast, the category 6c behaviour illustrates the inability to withstand pressure, thus heading towards failure state. Such behaviour can be identified as non-resilient behaviour.

In a water supply system, a storage reservoir is the key component that responds most significantly to adverse pressures arising from climate change. As Watts *et al.* (2012) have conceptualised, failure of a reservoir due to drought can be expressed in terms of variation in output volume as illustrated in Figure 8.2. Understanding the behaviour of a storage reservoir is very important for assessing the systemic resilience of a water supply system. Figure 8.2a and Figure 8.2b distinguish low and high resilience characteristics of a reservoir with respect to failure under drought conditions.

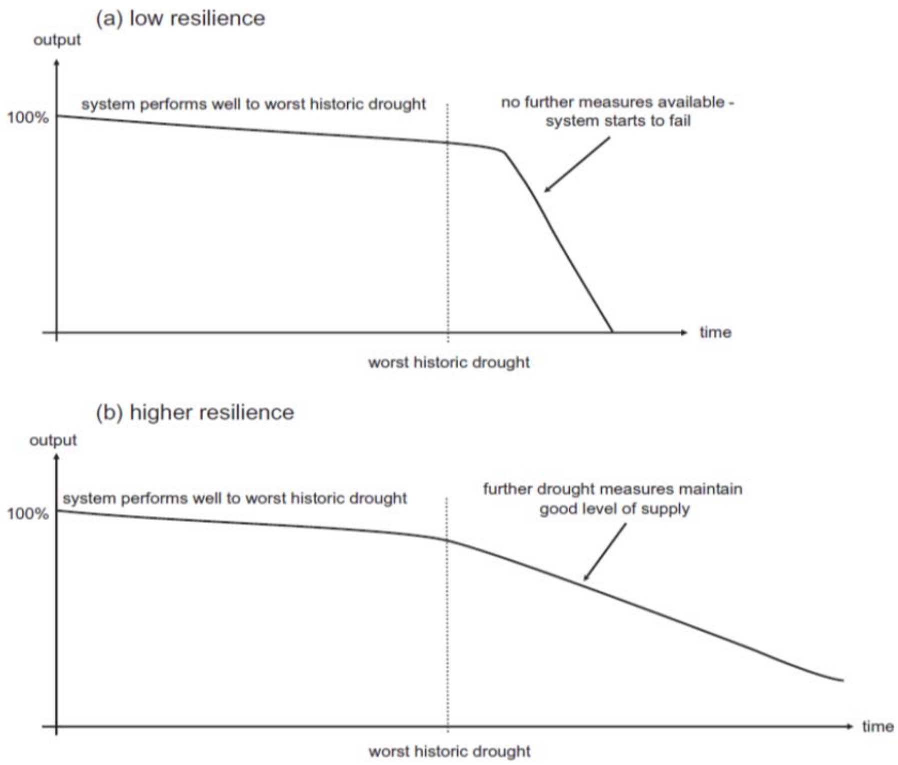


Figure 8.2- Conceptualised drought failure mode of a reservoir (adapted from Watts *et al.* 2012)

A system designed for the worst historic drought condition, might perform well until it faces a similar or even a worse drought, where the system might shift to a failure condition. A low resilience system tends to fail at a faster rate as shown in Figure

8.2a and a high resilience system tries to maintain a reasonable level of supply for a longer period as shown in Figure 8.2b. In this case, low and high resilience can be explained by the falling rate of output. Hence, low and high resilience behaviour refers to patterns 3b and 3c shown in Figure 8.1.

In assessing the output behaviour of a reservoir, understanding the characteristics of drought conditions in this case is important. The Australian Bureau of Meteorology defines drought as *a prolonged, abnormally dry period when there is not enough water for users' normal needs* (BOM 2013). With respect to the functionality of a water supply system, Watts *et al.* (2012) noted that droughts could be classified by their magnitude (dryness) and duration, but the sequencing of drier and wetter periods within a drought can be very important for the performance of a water supply system. Hence, two drought periods with the same metrics (return period, duration, and magnitude) could give rise to different behaviour of the same water supply system.

8.3 BEHAVIOUR UNDER DIFFERENT SCENARIOS

The operational characteristics of a water supply system as defined in this study were, the ability to withstand pressure and the speed of recovery of the system. The pressures were climate change and population growth impacts. The consequence of population growth considered was the increase in demand. As the intention was to evaluate the ability of the system, the supply potential of the system irrespective of the demand was evaluated. Therefore, the model was designed to indicate the maximum possible output, irrespective of the demand. The volume of output production was determined by the storage volume for which climate change was the main pressure, considering that the full system demand is extracted whenever available; otherwise the maximum available volume is extracted.

The population growth impact is reflected in the defined failure criteria. At higher population, the failure threshold was higher. Accordingly, the system reached the failure threshold faster. Hence, the population growth impact was reflected in the failure analysis, together with climate change impacts in Chapter 9 based on the system behaviour evaluated in the sections given below.

As the system behaviour evaluation was carried out using model simulations, the climate change pressures that apply at level 1 of the meta-system illustrated in Figure 1.2 were represented by changing the model input parameters. Different sets of input parameters created different scenarios for model simulations. The scenarios were selected in order to evaluate system behaviour under critical water availability conditions.

The consequence of low rainfall is inadequate water availability. However, despite short term low rainfall conditions, a high volume of stored water availability can minimise service failures. In view of this, for assessing the resilience capabilities of the system, operational status under different initial storage conditions were evaluated. The following storage conditions in reference to full storage capacity were considered:

- Combined reservoir storage level of 0% of full capacity
- Combined reservoir storage level of 50% of full capacity
- Combined reservoir storage level of 100% of full capacity

Under each of the above initial storage conditions, two rainfall scenarios were evaluated. The two rainfall scenarios were termed as '***reduced rainfall conditions'*** and '***drought periods'***. Reduced rainfall conditions were generated by reducing a pre-selected percentage of rainfall from 'average rainfall'. The percentage reduction was applicable for the entire duration of simulation and was primarily used for replicating potential future climate change impacts on rainfall. The term '***average rainfall'*** used in this Chapter refers to the 'typical year' monthly rainfall as discussed in Section 6.3.1.

A drought period was defined as a set period of extremely low rainfall rather than an average rainfall within the reference period. In other words, a drought is a period of unusually dry weather that persists long enough to cause environmental or economic problems, such as crop failure and water supply shortages. Because of the gradual development of dry conditions and the uneven impact on different regions, there is no agreed approach to pinpoint when a drought begins or ends, or to objectively assess its severity.

The generation of average rainfall metrics would normally include statistical analysis of monthly rainfall using long-term records. For example, in order to create average rainfall for January, the mean of all January rainfall values for the recorded period was considered. However, as the SEQ Water Grid was modelled as a stochastic system, it provided different outputs in terms of volume of potable water for different simulations.

The simulation results represent the behaviour under average weather conditions (no extreme events). As rainfall is subject to variation, normal behaviour cannot be expected at all times. Therefore, 100 simulations were generated for the same input parameters to create a sample population. The 100 simulations gave 100 different output conditions to incorporate the variations of rainfall, as the model has stochastic properties.

The lowest output for a month obtained from the 100 simulations was considered as the lowest possible expected output for that particular month. Similarly, the minimum output for each month obtained from the 100 simulations was considered to represent the expected lowest output for each month. The output pattern generated by the lowest expected output (observed from 100 simulations) for each month was the worst observed scenario. Therefore, such a scenario was termed here as the '***worst observed behaviour'.*** The following evaluations were based on the worst observed behaviour output levels.

As noted by the Queensland Government (2012), the best estimate (50^{th} percentile) projections of rainfall for the SEQ region show a decrease in the future, reference to the historical mean rainfall of 1971-2000. For incorporating climate change impacts and in view of evaluating the conditions described by *non-failure pressure increment percentage* (explained in Section 7.3.1), the behaviour of the system was evaluated in steps of 10% rainfall reduction for each storage condition.

Two drought conditions of six months and twelve months were considered for evaluating the ability of the system to recover after a short-term, low rainfall event. Only two possible drought periods (six months and twelve months) were considered in this study as it was not practicable to consider all possible drought periods. The droughts were considered only for 50% initial storage levels because under 0%

initial storage, the initial supply potential was below the failure threshold. Therefore, it was not possible to distinguish the recovery period from the effect of drought and the initial water shortage. For 100% storage, it was estimated that the system is unlikely to fail during a six months or 12 months drought, due to availability of sufficient storage. Therefore, the droughts were considered only for 50% storage levels with 100% average rainfall conditions because it is the most likely scenario applicable to current circumstances. Accordingly, the system behaviour was evaluated under the following scenarios as given in Table 8.1.

Table 8.1 – System behaviour evaluation scenarios

	Initial storage		
	0%	**50%**	**100%**
Rainfall (as a % of average rainfall)	**Drought period considered**	**Drought period considered**	**Drought period considered**
100%	Drought period not considered	Six months Twelve months	Drought period not considered
90%	Drought period not considered	Drought period not considered	Drought period not considered
80%	Drought period not considered	Drought period not considered	Drought period not considered
70%	Drought period not considered	Drought period not considered	Drought period not considered
60%	Drought period not considered	Drought period not considered	Drought period not considered
50%	Drought period not considered	Drought period not considered	Drought period not considered
40%	Drought period not considered	Drought period not considered	Drought period not considered
30%	Drought period not considered	Drought period not considered	Drought period not considered
20%	Drought period not considered	Drought period not considered	Drought period not considered

The reduced rainfall conditions under different initial storage levels were evaluated in order to determine the system's ability to withstand the pressure of low rainfall conditions. Non-failure under pressure indicates higher ability to withstand pressure. The pressure referred to here is the low rainfall condition.

The behaviour (output variations) of the SEQ Water Grid model under the scenarios mentioned above is discussed in the following sections. Sections 8.3.1, 8.3.2 and 8.3.3 below discuss the results of 0% storage, 50% storage and 100% storage conditions, respectively, of the SEQ Water Grid model simulations. In all the simulations, it was considered that when the system was below full supply potential, the system supplied the maximum available water to the consumers.

8.3.1 Combined reservoir storage level of 0% of full capacity level

For 0% initial storage level, the system behaviour under average rainfall and reduced rainfall (without drought) conditions were evaluated and the behaviour characteristics are discussed below.

A: Average rainfall without drought conditions (0% initial storage)

When the reservoir storage was 0%, initially the system was unable to operate at full supply potential. However, as the reservoirs started to fill, the supply potential increased gradually. No drought conditions were considered for this scenario. The system behaviour observed through model simulation (for average rainfall) is shown in Figure 8.3.

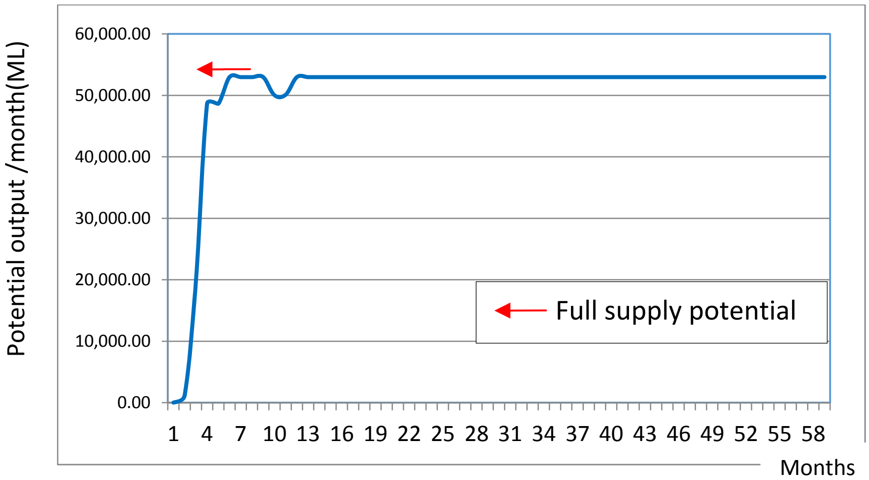


Figure 8.3 – Simulated results showing behaviour of SEQ Water Grid under average rainfall for 0% storage conditions

Under normal climate conditions (without a prolonged dry period), the system returned to full supply potential within five months. However, in the case where the actual demand was less than the 100% operational capacity, due to monthly extractions being less, the system might achieve the full supply potential at a much faster rate as the monthly water savings are accumulated. In order to account for uncertainty of rainfall, the worst observed scenario was evaluated. Figure 8.4 shows the worst observed behaviour of the system for 0% initial storage conditions.

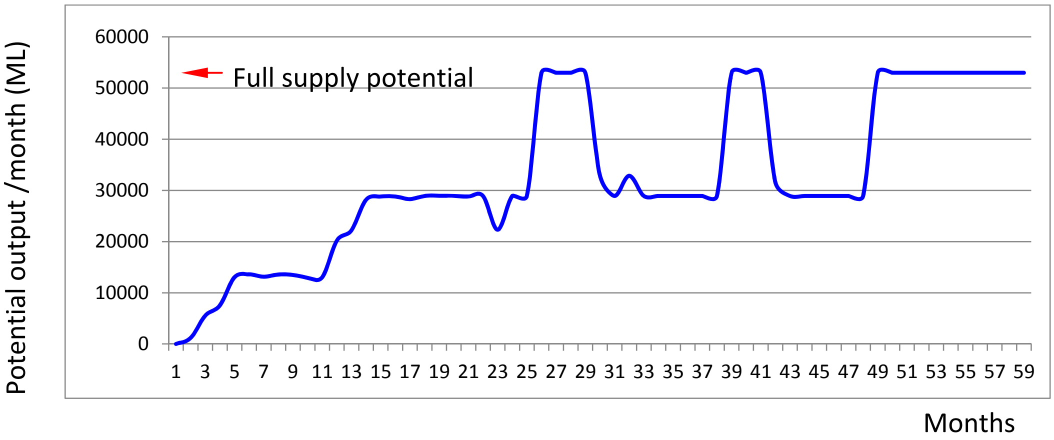


Figure 8.4- Simulated results showing worst observed behaviour of SEQ Water Grid under average rainfall for 0% storage conditions

As evident from Figure 8.4, which shows the worst observed behaviour, it is reasonable to expect that the maximum period the system takes for stabilisation is approximately 48 months (for 0% initial storage) considering the uncertainty of rainfall. It was assumed that during this period the system supplied the maximum amount of available water to the consumers.

B: Reduced rainfall without drought conditions (0% initial storage)

Figure 8.5 shows the worst observed system behaviour for further rainfall reducing steps of 10% at a time.

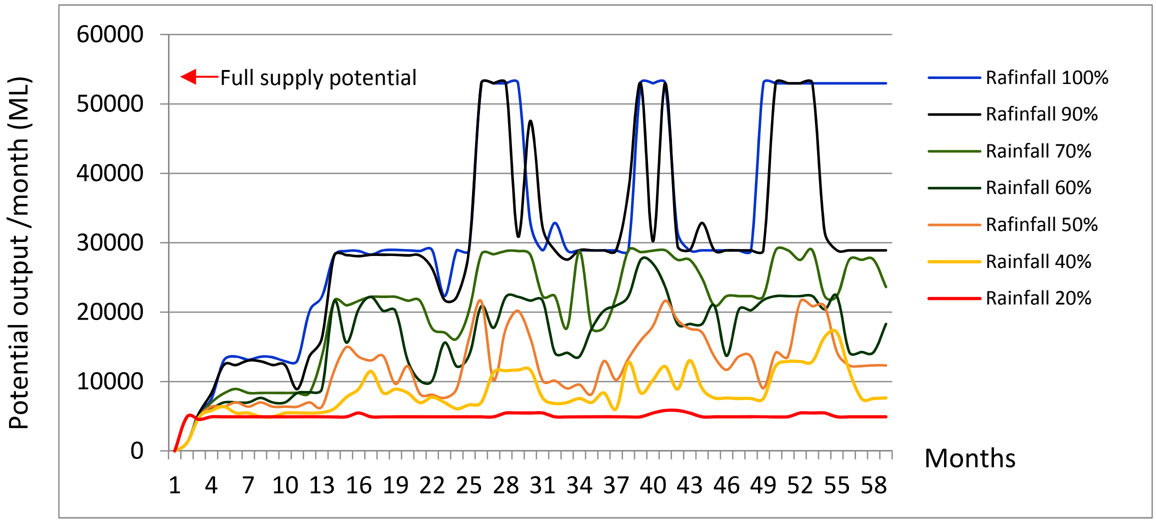


Figure 8.5- Simulated results showing the worst observed behaviour of SEQ Water Grid under reducing rainfall below average for 0% storage conditions

Figure 8.5 shows that as the rainfall reduces, the supply potential of the system gradually decreases. Ten percent drop of rainfall from average, increased the period for stabilisation from 48 to 60 months. It was considered that during this period, the system supplied the maximum available water to the consumers. When the rainfall dropped to 50% or lower, the supply potential of the system dropped significantly.

8.3.2 Combined reservoir storage level of 50% of full capacity level

When the reservoir storage was at 50% capacity, the system did not depend on rainfall until the storage (available volume) became equal to the maximum demand, because 50% of capacity volume was higher than the maximum demand. Therefore, as far as the storage was sufficient to meet the maximum demand, the system was capable of operating at 100% supply, irrespective of the rainfall conditions.

A: Average rainfall without drought conditions (50% initial storage)

The system behaviour was evaluated under average rainfall (without extreme climatic conditions) for 50% initial storage and the supply potential as shown in Figure 8.6

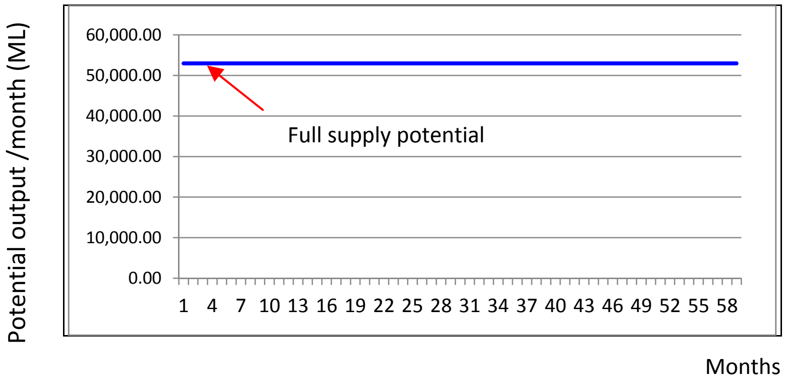


Figure 8.6- Simulated results showing behaviour of SEQ Water Grid under average rainfall for 50% storage conditions

Figure 8.6 shows that the system is very stable (under 100% of average rainfall and 50% storage) as it has the ability to continue operation at full supply potential. However, it should be noted that 50% storage of the SEQ Water Grid contains a very large volume of water because the system has a very large storage capacity. Hence, the SEQ Water Grid is able to maintain a high level of stability. However, depending on the full storage capacity of the system, a different system might not show the same level of stability for 50% storage level. Systems with low storage capacity might need higher percentage storage to achieve the same level of stability.

B: Average rainfall with drought of six months and twelve months (50% initial storage)

The stability in the performance could be expected to reduce during drought periods. Two scenarios (six months of **no** rainfall period and twelve months of **no** rainfall period) were tested to represent drought periods at the 50% storage conditions. The worst observed behaviour of the simulated results for these two scenarios are shown in Figure 8.7.

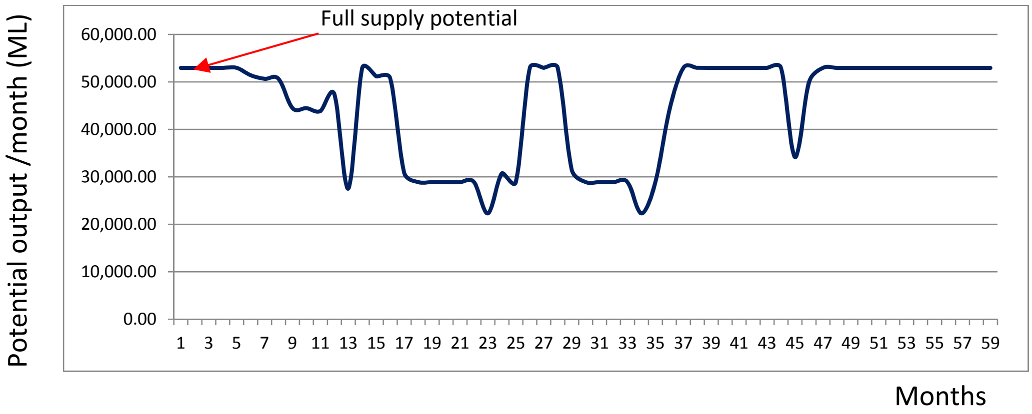


Figure 8.7 (a)-Simulated results showing the worst observed behaviour of SEQ Water Grid subjected to a six month no rainfall period at 50% storage

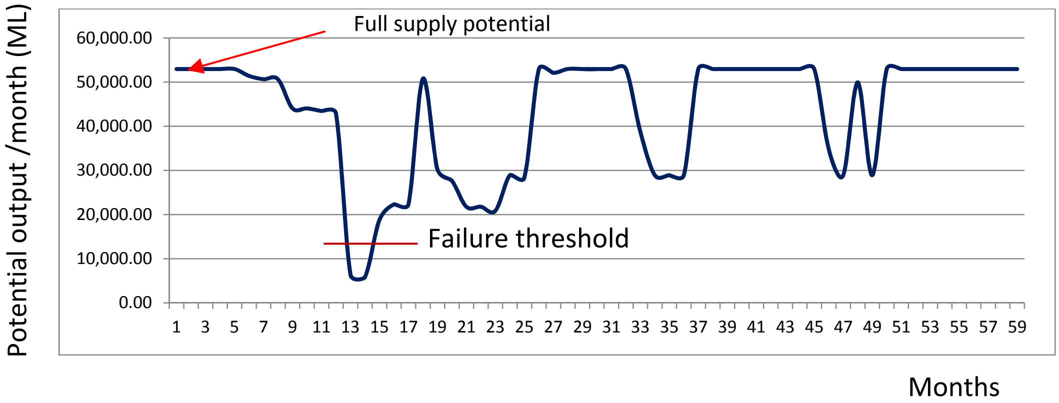


Figure 8.7 (b)- Simulated results showing the worst observed behaviour of SEQ Water Grid subjected to a twelve month no rainfall period at 50% storage

The above figures show that although the system was stable when there were no drought conditions (Figure 8.6), the supply potential dropped after 7 months for a prolonged drought period of six months (Figure 8.7a). The time taken to establish stability increased up to 48 months. Figure 8.7b shows the behaviour of the system for a 12 month drought period. It shows that the system has lost the ability to produce output significantly and has taken up to 50 months to return to stable conditions.

C: Reduced rainfall without drought conditions (50% initial storage)

For evaluating the system behaviour under reduced rainfall (without extreme climatic conditions), simulations were undertaken for rainfall reduced levels in 10% steps from the average rainfall. It was noted that for 50% storage conditions, the system was very stable until the rainfall dropped to 70% of average rainfall (which was quite different behaviour to that for 0% storage conditions). Accordingly, the worst observed output levels below 70% average rainfall are shown in Figure 8.8.

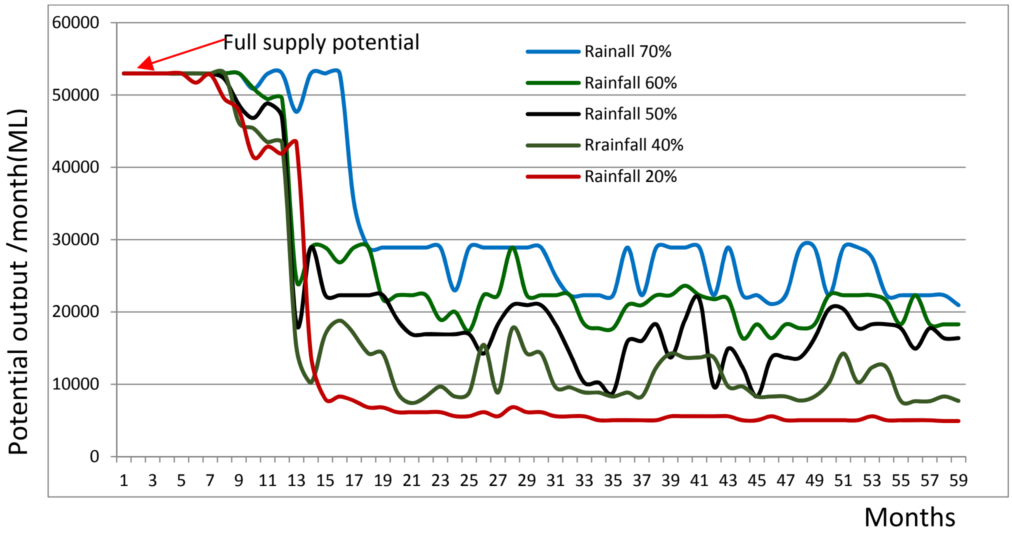


Figure 8.8- Simulated results showing the worst observed behaviour of SEQ Water Grid under reducing rainfall for 50% storage conditions

Figure 8.8 shows that when the rainfall was 70% of the average rainfall (30% reduction in rainfall) for 50% storage, the system dropped the ability to maintain full supply potential within 15 months. For a further 50% reduction (20% average rainfall) of rainfall, the system could maintain above 80% of full supply potential for a 10 month period. However, the rate of supply drop was very high. This indicates that the system’s ability to maintain supply can drop quite rapidly. Therefore, timely water conservation measures would need to be introduced to prevent a catastrophic failure of the system.

8.3.3 Combined reservoir storage level 100% of full capacity level

For 100% storage level, the system showed high ability to operate at full supply potential. As the system contained sufficient water to operate at full operational capacity, dependability on rainfall is low.

A: Average rainfall without drought conditions (100% initial storage)

Under average rainfall conditions, the system showed highly stable behaviour as illustrated in Figure 8.6. Even for the worst case scenario, the capability to perform at full supply potential did not drop.

B: Reduced rainfall without drought conditions (100% initial storage)

Above 70% of average rainfall, the system was very stable and is able to operate at full supply potential. The system behaviour becomes unstable for rainfall below 70% of average rainfall. The supply potential of the system below 70% of average rainfall is shown in Figure 8.9

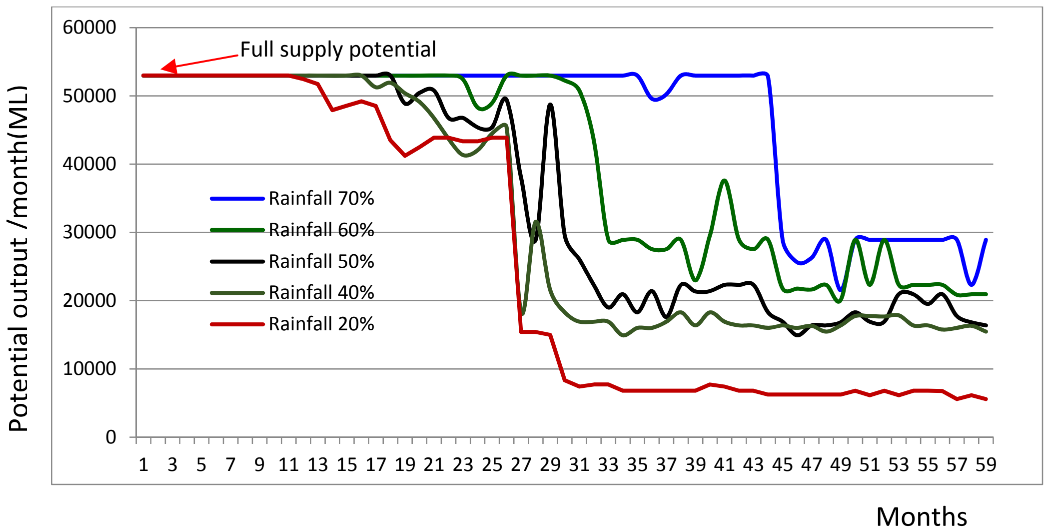


Figure 8.9- Simulated results showing the worst observed behaviour of SEQ Water Grid under reducing rainfall for 100% storage conditions

For 70% of average rainfall conditions, the system manages to maintain 100% operational conditions for 42 months against a 15 month period in the case of 50% storage level. However, a further 10% drop in rainfall, reduced the stable period to 30 months, which is a considerable reduction in time of the stable period.

8.4 RESILIENCE CHARACTERISTICS IDENTIFIED BY SYSTEM BEHAVIOUR

The intention for evaluating system behaviour was to determine its capability for withstanding pressures exerted by climate change and population growth impacts. The above analysis shows that the reservoir storage volume is a governing condition for maintaining the stability of the system. Therefore, withstanding and recovering capacity to provide water supply depends on the available storage. The importance of this fact from a management perspective is that it highlights the necessity of identifying trigger points linked to storage levels. This approach will provide the opportunity to take timely precautionary actions in order to avoid catastrophic system failures. The SEQ Water Grid, which has a large storage capacity, was predicted to recover within a relatively short period (of five months) under normal operating conditions for an initial storage level of 0%.

Due to the uncertainty imposed by climate conditions, it is difficult to predict the behaviour by observing one behaviour pattern obtained by a single model simulation. Therefore, the SEQ Water Grid model was developed to incorporate the uncertainty of rainfall for enabling stochastic simulations. Furthermore, the analysis was carried out for the worst observed scenario. Therefore, the evaluation undertaken was based on critical conditions.

For 50% of full capacity storage, the system showed very consistent stable conditions. The system was capable of sustaining functionality even for extremely low rainfall conditions lasting six months without going into very low supply levels. However, for a twelve month extreme drought conditions (no rainfall), the system reached the failure state. The failure state defined in this study is the inability to supply at least 50% of the demand. As the annual demand on the SEQ Water Grid is 290,000 ML(Spiller *et al.* 2011), 50% of monthly demand accounts for 12,000 ML. However, the system regained supply potential above failure threshold level within a two month- period as evident in Figure 8.7b. Therefore, for storage levels above 50% of full capacity, unless for a long term drought period (more than 12 months), a catastrophic failure is an unlikely event.

For 100% of full capacity storage, even for the worst expected rainfall conditions the system demonstrated that it was able to operate at full supply potential for a period of 45 months (Figure 8.9) with 70% average rainfall. Therefore, system failure had a low probability of occurrence. However, a notable behaviour of the system was the high rate of output decrease, indicating rapid loss of resilience after reaching the trigger point. Therefore, in order to avoid catastrophic failure, water conservation measures may be enforced at the trigger point.

It is important to understand that, although the available storage is a significant influential factor for determining output levels, the percentages considered in this study (0%, 50% or 100%) were only an indication of the storage of water availability. The storage capacity varies in different water supply systems. Even a higher percentage of storage in a system with a smaller storage capacity may not show the same degree of stability as shown in the above results. For example, the SEQ Water Grid was stable even in the worst case scenarios under average rainfall and 50% storage due to its high storage capacity. The system was not dependent on rainfall for a considerable period of time as the 50% storage held a large volume, which was adequate for satisfying demand assuming that there was no rapid increase in demand due to population growth. The system behaviour is further discussed in the next chapter with a view to focusing on critical management decision making.

8.5 CONCLUSIONS

The behaviour of a water supply system under different scenarios can be used to explain the resilient characteristics of the system. A real-world system (SEQ Water Grid) was modelled and simulated under different pressures (that represent different climate conditions) to evaluate the system behaviour. The purpose of obtaining the system behaviour in terms of supply potential under different climate conditions was to analyse against population growth impacts in order to evaluate systemic resilience to these two pressures, which is discussed in Chapter 9.

Although the volume of rainfall was considered as the main climate parameter, available storage contributes in a significant manner to enhance system capability to maintain performance. This can be explained by comparing the simulated results of 50% and 100% storage conditions for the SEQ Water Grid for the same reduced rainfall levels (70% of average) as an example. For 70% average rainfall conditions (30% reduced), the system managed to maintain full operational potential for 42 months at 100% storage level, but reduced the period to 15 months for 50% storage level. Consequently, this confirmed that the stability of the system was highly dependent on available storage.

The following points should be noted from the simulated results.

- Although an excessive storage capacity acts as a redundancy factor under normal climate conditions, it contributes to enhance system capability to maintain system performance in a crisis situation.
- When the output (service) drops due to pressure, it is important to have prior knowledge of the magnitude of pressure (level of rainfall reduction) when the system starts to reduce service potential so that appropriate management strategies can be adapted to avoid catastrophic failure.

Chapter 9: Resilience Assessment for Decision Making

9.1 BACKGROUND

Resilience assessment of a system informs the systemic properties that are important for management. The outcome of the assessment process should interpret the level of systemic resilience with reference to a defined baseline. Accordingly, a set of indicators were proposed in Chapter 7 to evaluate systemic resilience of a water supply system and an approach for selecting suitable indicators was also proposed. The SEQ Water Grid, which was discussed in Chapter 5, was the selected case study. A system dynamics model was developed to model the SEQ Water Grid and the modelling procedure was discussed in Chapter 6. The system behaviour, expressed in terms of output variations, was evaluated in Chapter 8.

This chapter further discusses how the system behaviour could be used for resilience assessment. However, as identified in previous chapters, the interpretation of resilience in numerical terms, without reference to critical thresholds, is not helpful from a management perspective. This is due to non-existence of standard numerical criteria for resilience. Therefore, systemic resilience was expressed in this study as a relative condition of 'high' or 'low' level of resilience. Through resilience assessment, it is possible to understand the system's ability to withstand pressures acting on the system. High resilience systems minimise service failures under pressure. As prudent decision making is critical to avoid service failures in infrastructure management, prior knowledge of systemic resilience provides decision makers with confidence to make appropriate decisions based on the system's ability to adapt to changes.

9.2 ASSESSMENT PROCESS

Resilience of the case study water supply system was assessed in terms of the 'ability of the system to withstand pressure' and 'ability to recover'. The following sections discuss the assessment process in detail by analysing behaviour of the SEQ Water Grid System under difference simulated scenarios.

9.2.1- Ability of the system to withstand pressure against failure threshold

The following indicators proposed in Chapter 7, were used to evaluate the system's ability to withstand pressure for 50% and 100% initial storage levels.

- Non-failure rainfall reduction percentage
- Designed pressure to threshold pressure ratio (R_{pp})
- Service reduction ratio (R_{ss})
- Service reduction rate (R_{sp})

A: Initial storage of 50% of full capacity

(i) Non-failure rainfall reduction percentage

The terms 'non failure' and 'rainfall reduction percentage' are further explained for clarity. 'Non failure' means 100% certainty of the system not moving into failure state. For absolute certainty of non-failure, the worst observed behaviour (explained in Section 8.3) was considered for evaluation. 'Rainfall reduction percentage' refers to the reduction in percentage rainfall with respect to the average rainfall over the entire period of simulation. Reduction in rainfall was undertaken considering future climate change projections as explained in Section 8.3. Figure 9.1 shows the inclusion of the failure threshold in the system behaviour graph (Figure 8.8) for evaluating failure conditions. The method of development of the system behaviour graph, based on which Figure 9.1 was developed, and the reason for showing rainfall between 20% and 70%, were explained in Section 8.3.

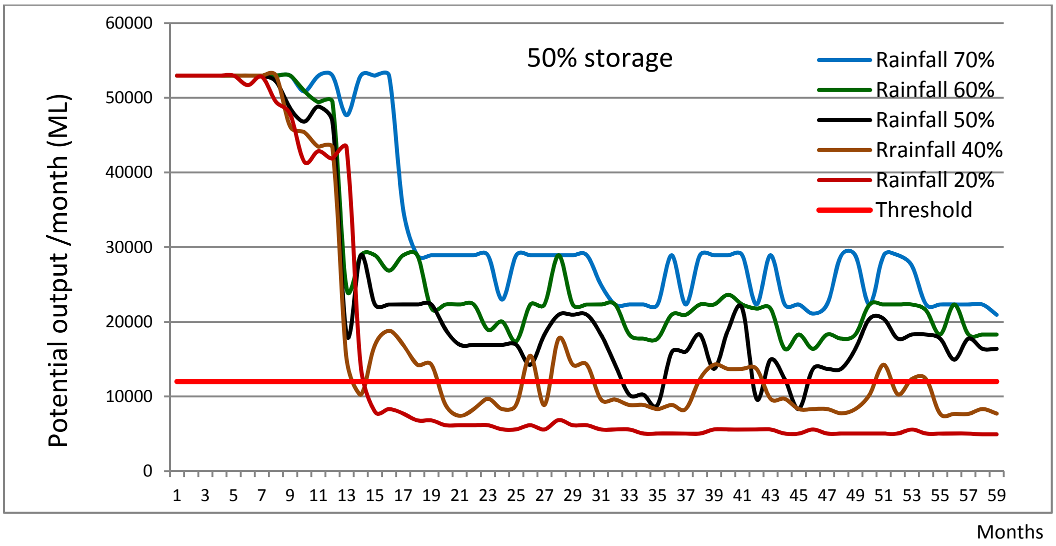


Figure 9.1- The worst observed system behaviour under different rainfall conditions with reference to the failure threshold (simulated results for SEQ Water Grid for 50% storage)

Figure 9.1 shows that for 50% storage, the system has not failed although the rainfall is reduced up to 60% of the average rainfall (40% reduction from average). However, the system fails when the average rainfall is reduced by further 10% (50% reduction from average). Therefore, the ***non-failure rainfall reduction percentage*** was considered as 40% (the maximum allowable percentage of rainfall reduction without failure).

(ii) ***Designed pressure to threshold pressure ratio (R_{pp})***

Reduction in rainfall translates to an increase in pressure. Assuming a linear relationship, the magnitude of pressure increase was equated to the magnitude in rainfall decrease. The threshold pressure was identified by the previous indicator as 40% below average rainfall. Therefore, the increase in pressure was considered as 40% increase above average. Considering the designed pressure, P_d as the average rainfall (100%), the threshold pressure P_t becomes 140%.

Accordingly, the value of Ratio (R_{pp}) = $\frac{Pt-Pd}{Pd}$, becomes 0.4.

where P_t- threshold pressure for the system

P_d – design pressure

This indicates that in terms of pressure (on the system), the system is capable of operating even 0.4 times above the average pressure without shifting to failure state.

(iii) ***Service reduction ratio (R_{ss})***

$$\text{Ratio } (R_{ss}) = \frac{\mathbf{Smin}}{Sf},$$

where S_{min} - minimum level of service at threshold pressure

S_f - full service capacity

This ratio indicates the supply potential at threshold pressure compared to the full service capacity. Considering the minimum output value (S_{min}) for each of the 100 simulations and the full service capacity (S_f) of the system, R_{ss} values were computed and the result is given in Figure 9.2. The lowest R_{ss} value of the 100 simulations is given below in order to determine the range of R_{ss} values. The lowest R_{ss} value was calculated by using the lowest S_{min} value (least observed output value) of the 100 simulations which was 16,375.5 and the S_f (full supply potential), 52, 973, which are given in Appendix C.

$$R_{ss} \text{ (lowest)} = \frac{\mathbf{Smin}}{Sf},$$

$$= 16{,}375.5/52{,}973$$

$$= 0.31$$

Therefore the R_{ss} value lies between 0.31 and 1 for 50% storage (Figure 9.2).

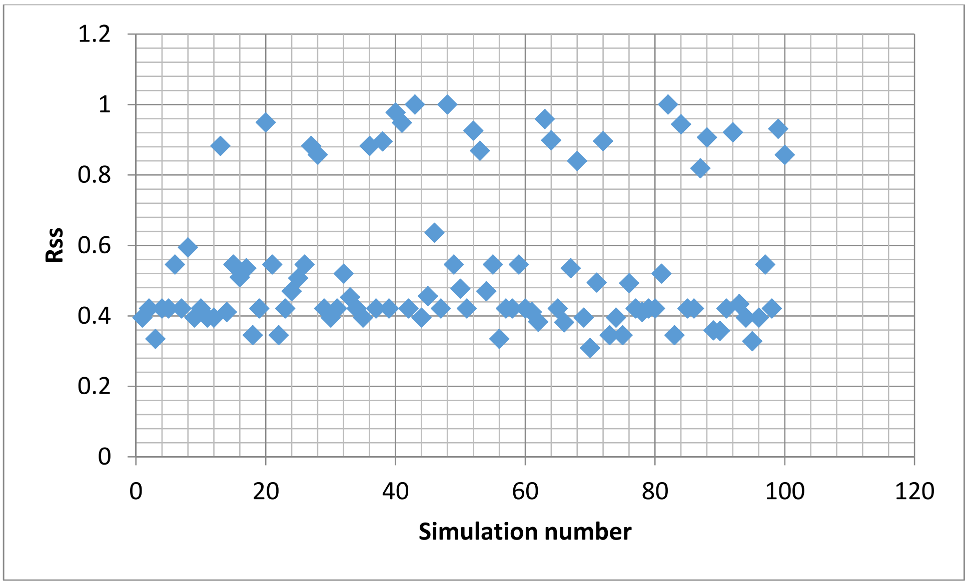


Figure 9.2- Service reduction ratio (R_{ss}) values for SEQ Water Grid for 100 simulations (50% storage)

Figure 9.2 shows that for 40% reduction in rainfall (the threshold pressure for 50% storage), for most of the time, the indicator value (R_{ss}) is scatted around 0.4 and some values are close to 1. The R_{ss} values should range from 0 to 1 and higher values indicate that even at the threshold pressure, the system is capable of supplying the services close to full supply potential. Accordingly, at the threshold pressure limit of rainfall 40% below average rainfall, at times the SEQ Water Grid is capable of providing a full level of services, which corresponds to the indicator value being equal or close to unity.

(iv) Service reduction rate (R_{sp})

$$\text{Ratio } (R_{sp}) = \frac{(Sf - Smin)/Sf}{(Pt - Pd)/Pd},$$

where S_f – full service capacity

S_{min} – minimum level of service at threshold pressure

P_t – threshold pressure for the system

P_d – design pressure

This indicator explains the sensitivity of the service reduction due to change of pressure. A higher value indicates a high rate of response to pressure change. The design pressure (P_d) was considered as the average rainfall (100%) and the threshold pressure (P_d) as 40% below average rainfall, which is equated to an increase of pressure by similar magnitude. That translates to an increase in pressure up to140%. S_f is system specific, which is the full supply capacity. Considering the S_{min} value of each of the 100 simulations, the indicator (R_{sp}) values were computed and plotted on a graph as shown in Figure 9.3.

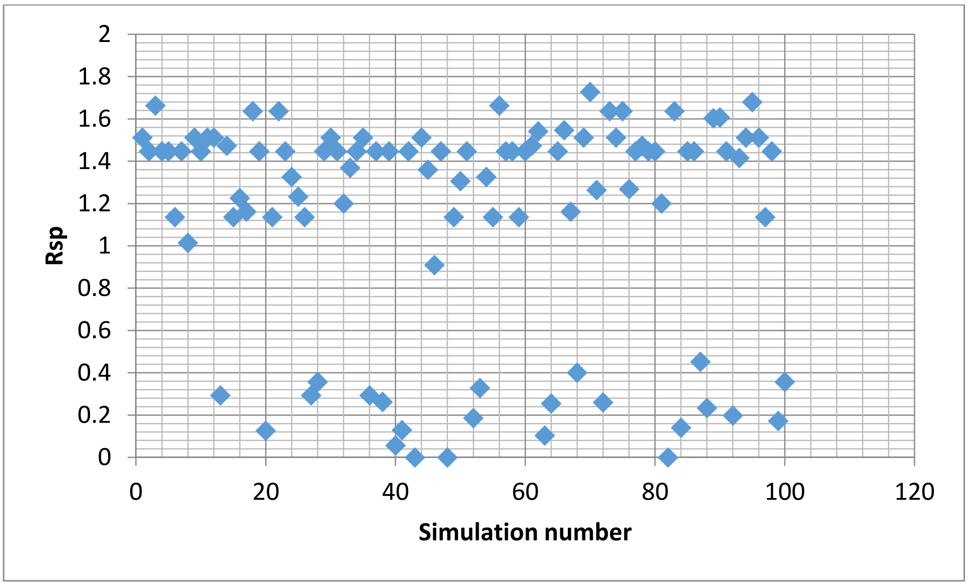


Figure 9.3- Service reduction rate values for SEQ Water Grid for 100 simulations (50% storage)

The highest R_{sp} value corresponds to the lowest S_{min} value. Low R_{sp} values close to 0 indicate that the rate of service change as a response to pressure change is low. The highest R_{sp} value of the 100 simulations is given below. The lowest S_{min} value and S_f were obtained from model simulations given in Appendix C

$$R_{sp}\,(\text{highest}) = \frac{(Sf-Smin)/Sf}{(Pt-Pd)/Pd},$$

$$= \frac{(52{,}973-16{,}375.5)/52{,}973}{40/100}$$

$$=1.73$$

Therefore the indicator value lies between 0 and 1.73.

Figure 9.3 shows that the R_{sp} values are primarily scatted around 1.4. R_{sp} values close to 0 in some instances indicate that the SEQ Water Grid has a low service reduction rate with the increase in pressure.

B: Initial storage of 100% of full capacity

Similar to the indicator values obtained for 50% storage, the indicator values for 100% storage were obtained as explained below. The first step was to determine non-failure rainfall reduction percentage for 100% storage. The system behaviour graph for 100% storage was developed as explained in Section 8.3.3B and the failure threshold was included to derive Figure 9.4.

(i) Non-failure rainfall reduction percentage

Figure 9.4 shows the worst observed behaviour obtained from 100 simulations for 100% storage including the failure threshold.

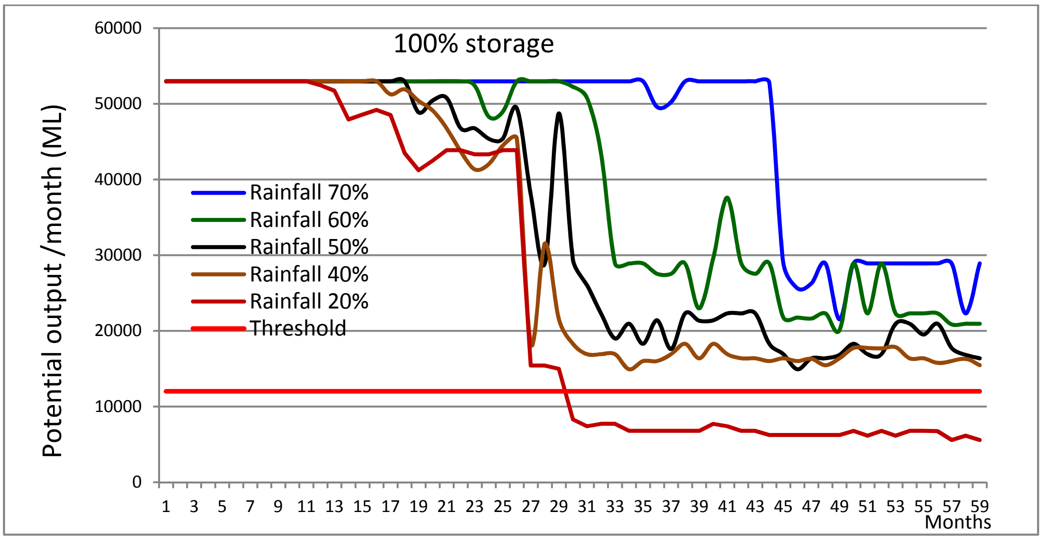


Figure 9.4- The worst observed system behaviour for different rainfall conditions with reference to the failure threshold (simulated results for SEQ Water Grid for 100% storage)

Figure 9.4 shows that the system did not fail until the rainfall reduces up to 40% of average rainfall. This means that the system has the ability to withstand a 60% reduction in rainfall. Hence, the *'non failure rainfall reduction percentage'* was considered as 60% for 100% initial storage level. This reveals that the threshold pressure was 160% as explained in the case of 50% storage.

(ii) Designed pressure to Threshold pressure ratio (R_{pp})

$$\text{Ratio } (R_{pp}) = \frac{Pt-Pd}{Pd},$$

where P_t- threshold pressure for the system

P_d – design pressure

Since the term (P_t- P_d) is equal to 160%, the ratio value becomes 0.6.

(iii) ***Service reduction ratio (R_{ss})***

$$\text{Ratio } (R_{ss}) = \frac{\mathbf{Smin}}{\boldsymbol{Sf}},$$

where S_{min} - minimum level of service at threshold pressure

S_f - full service capacity

Considering the minimum output value (S_{min}) for each of the 100 simulations and the full service capacity (S_f) of the system, R_{ss} values were computed and the distribution is given in Figure 9.5. The lowest R_{ss} value of the 100 simulations is calculated below in order to determine the range of R_{ss}. The lowest observed output value (S_{min}) of the 100 simulations was 14,926 and the full supply potential (S_f) was 52, 973 which are given in Appendix C.

$$R_{ss} \text{ (Lowest)} = \frac{\mathbf{Smin}}{\boldsymbol{Sf}},$$

$$= 14{,}926/52{,}973$$

$$= 0.28$$

Therefore, the R_{ss} value for 100% storage lies above 0.28 for 100% storage.

Figure 9.5 shows the R_{ss} values for 100 simulations

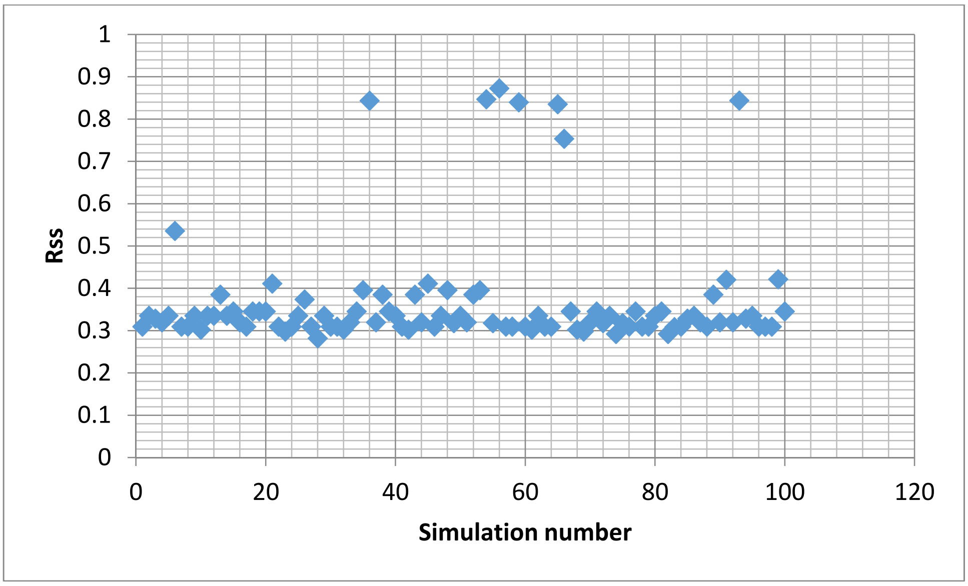


Figure 9.5- Service reduction ratio values for SEQ Water Grid for 100 simulations (100% storage)

In Figure 9.5 most of the R_{ss} values are scatted around 0.3. For 100% storage there are occasions with very small service reduction at threshold pressure (60% rainfall reduction) having R_{ss} value close to 0.9.

(iv) ***Service reduction rate (R_{sp})***

$$\text{Ratio } (R_{sp}) = \frac{(Sf - Smin)/Sf}{(Pt - Pd)/Pd},$$

where S_f – full service capacity

S_{min} – minimum level of service at threshold pressure

P_t – threshold pressure for the system

P_d – design pressure

Considering the S_{min} value of each of the 100 simulations, the R_{sp} values were computed and plotted on the graph as shown in Figure 9.6.

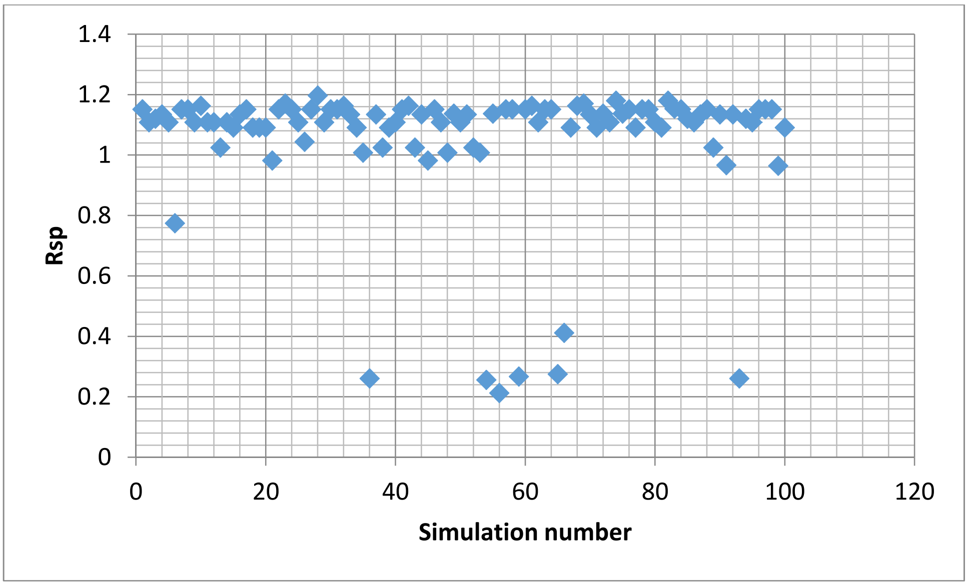


Figure 9.6- Service reduction rate values for SEQ Water Grid for 100 simulations (100% storage)

In Figure 9.6 the R_{sp} values are scatted around 1.2. Compared to Figure 9.3 (50% storage), R_{sp} has dropped from 1.4 to 1.2 indicating decrease in service reduction rate. The highest R_{sp} value of the 100 simulations was calculated and is given below. The values of S_{min} and S_f were obtained from model simulations given in Appendix C

$$\text{Ratio } (R_{sp}) = \frac{(Sf - Smin)/Sf}{(Pt - Pd)/Pd},$$

$$= \frac{(52{,}973 - 14{,}626)/52{,}973}{60/100}$$

$$= 1.2$$

Therefore the indicator value lies between 0 and 1.2.

9.2.2 Interpretation of indicators values

The indicator values for 50% and 100% initial storages are tabulated in Table 9.1.The non-failure rainfall reduction percentage of 40% indicates that the system is capable of withstanding pressure (low rainfall) even for 40% reduced rainfall conditions for 50% initial storage. For 100% initial storage, the pressure withstanding capability increased up to 60% reduced rainfall conditions. Additionally, the system has the ability to withstand 0.4 times above the 'design pressure' for 50% initial storage and 0.6 times above the 'design pressure' for 100% initial storage. The design pressure refers to the level of disturbance (pressure) that the system was expected (designed) to cope without failure. The pressure in this case was the low rainfall conditions.

A system that is capable of functioning without failure, even at low output level can be classified as a high resilient system. The supply potential of a system drops when the storage decreases. Therefore, during continuous operation, the supply potential of the system decreases. The service reduction ratio (R_{ss}) indicates the available service potential at the threshold pressure. For 50% initial storage, R_{ss} value of 0.31 indicates that the system has the ability to function without failure until the supply potential drops up to 31% of full supply potential. For 100% initial storage, the system is capable of providing services without failure until the supply potential reduces to 28% of the full supply potential. This indicates that the SEQ Water Grid has the ability to operate over a considerable range of pressure without failure, which indicates a high resilience characteristic.

Considering the service reduction rate (Rsp), the low R_{sp} values close to 0 indicate that the rate of service change as a response to pressure change is low. However, the model simulations of SEQ Water Grid have given comparatively high (above 1) service reduction rate. The high (above 1) service reduction rate of 1.73 and 1.2 indicates that the pressure variation has a significant impact on output variations of the system.

Table 9.1- System ability to withstand pressure for 50% and 100% storage

Indicator	50% Storage	100% Storage
Non-failure rainfall reduction percentage	40%	60%
Designed pressure to Threshold pressure ratio (R_{pp})	0.4	0.6
Service reduction ratio (R_{ss}) (at worst observed case)	0.31	0.28
Service reduction rate (R_{sp}) (at worst observed case)	1.73	1.2

9.2.3- Ability of the system to recover

The other selected resilience characteristic, the system's ability to recover under average rainfall conditions, is discussed in this section. For evaluation, time was considered as the measurable parameter. The worst observed behaviour was evaluated for:

- 0% storage (six month and twelve month low rainfall periods)
- 50% storage (six month and twelve month low rainfall periods)
- 100% storage (twelve month low rainfall period)

The two indicators, non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) were used for evaluation of the system's ability to recover. The SEQ Water Grid model simulations were carried out for a five year period. The low rainfall periods were characterised by 'zero' rainfall for the defined (six or twelve month) period and average rainfall for the rest of the five year period.

The worst observed system behaviour as explained in Section 8.3 for: (a) initial 0% storage (six and twelve month low rainfall periods); (b) 50% storage (six and twelve month low rainfall periods); and (c) 100% storage (twelve month low rainfall period) obtained from 50 simulations are discussed below.

A: Storage level 0% (six month low rainfall period)

Figure 9.7 shows the worst observed system behaviour obtained from 50 simulations for a six month low rainfall period including the failure threshold. Initially the supply potential was below the failure potential and gradually increased and reached the full supply capacity. As this was the worst observed behaviour, the recovery period shown in Figure 9.7 can be expected as the maximum duration that the system takes for recovery. Therefore, the maximum recovery period for a six month low rainfall period can be considered as 13 months, as shown in Figure 9.7.

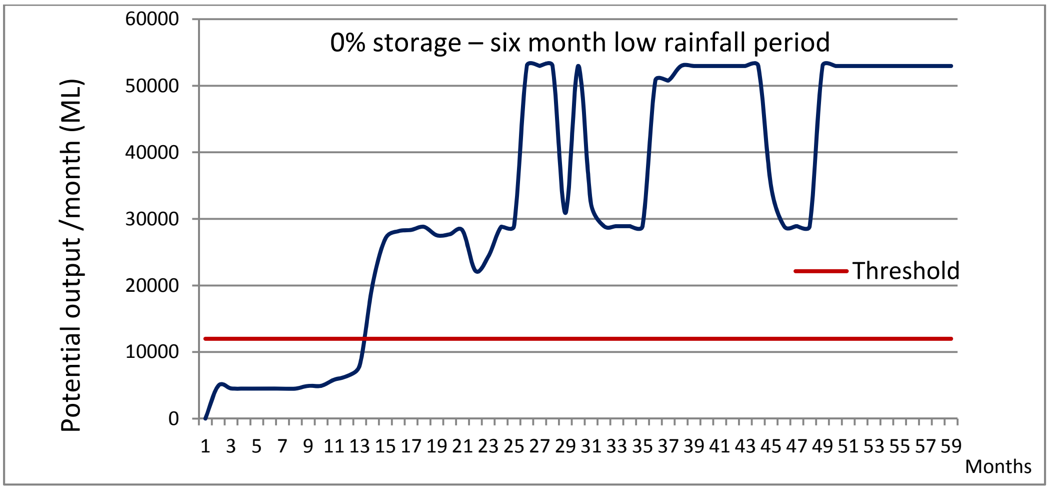


Figure 9.7 – The worst observed system behaviour for six months low rainfall period (simulated results for SEQ Water Grid for 0% storage)

R_{nf} and R_{rr} values for each simulation were calculated and given in Figure 9.8.

Non failure ratio (R_{nf}) $= \frac{\mathbf{Tnf}}{\boldsymbol{Tt}}$,

where T_{nf} –non failure duration

Tt – total observed duration and

Non- failure duration (months) for each simulation was considered for calculation and the total observed duration was 60 months, as the simulation period was five years. The simulation results are given in Appendix C.

Recovery ratio (R_{rr}) $= \frac{\boldsymbol{Sr}}{\boldsymbol{Sf}}$,

where S_r – level of service after recovery

S_f – full service capacity

It was observed that in each simulation (given in Appendix C) the output level had recovered up to full service capacity after the six month low rainfall period.

Therefore R_{rr} values become 1. Figure 9.8 shows the R_{nf} and R_{rr} values for 50 simulations.

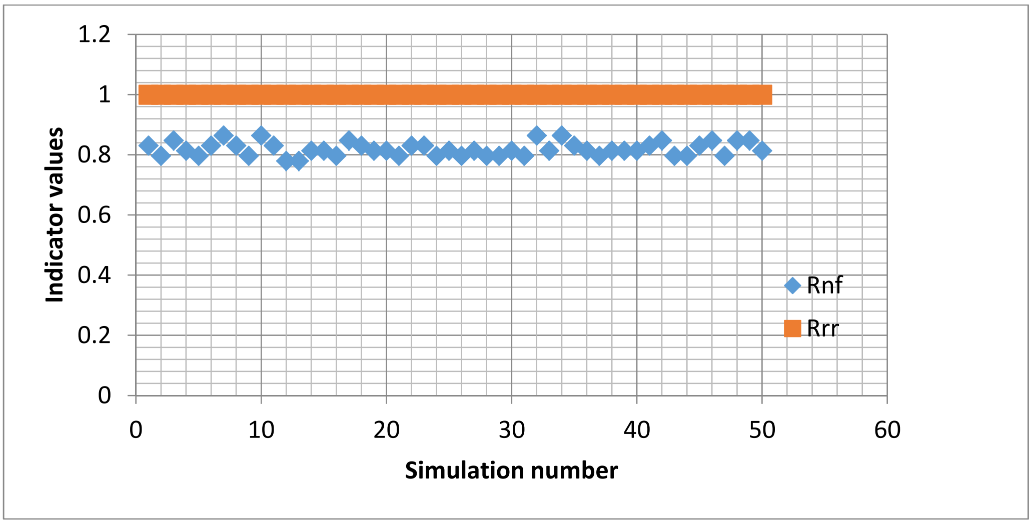


Figure 9.8 - non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for six month low rainfall period (SEQ Water Grid -0% initial storage)

As evident in Figure 9.8, a high non-failure ratio (R_{nf}) close to 0.8 indicates that the system shows high recoverability in terms of non-failure duration. R_{rr} value of 1 indicates that the system recovers up to the initial condition in terms of quantity (volume) of water available for supply.

B: Storage level 0% (twelve months low rainfall period)

Figure 9.9 shows the worst observed system behaviour obtained from 50 simulations for a 12 month low rainfall period including the failure threshold (for 0% storage).

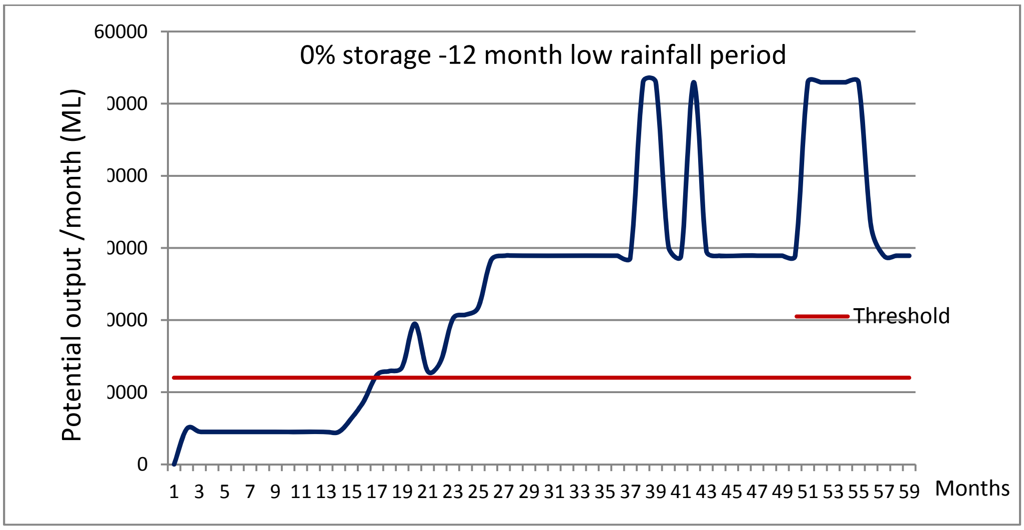


Figure 9.9 – The worst observed system behaviour for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 0% initial storage)

As evident in Figure 9.9, the maximum recovery period is approximately 17 months. Therefore, the results show that the system takes a considerable period of time to recover when the initial storage level is 0%. However, the system is capable of producing up to the full supply level and hence the level of service after recovery (S_r) becomes equal to the full supply capacity (S_f). Therefore, R_{rr} becomes 1. Figure 9.10 shows the non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for twelve months low rainfall period (0% initial storage) obtained for 50 simulations.

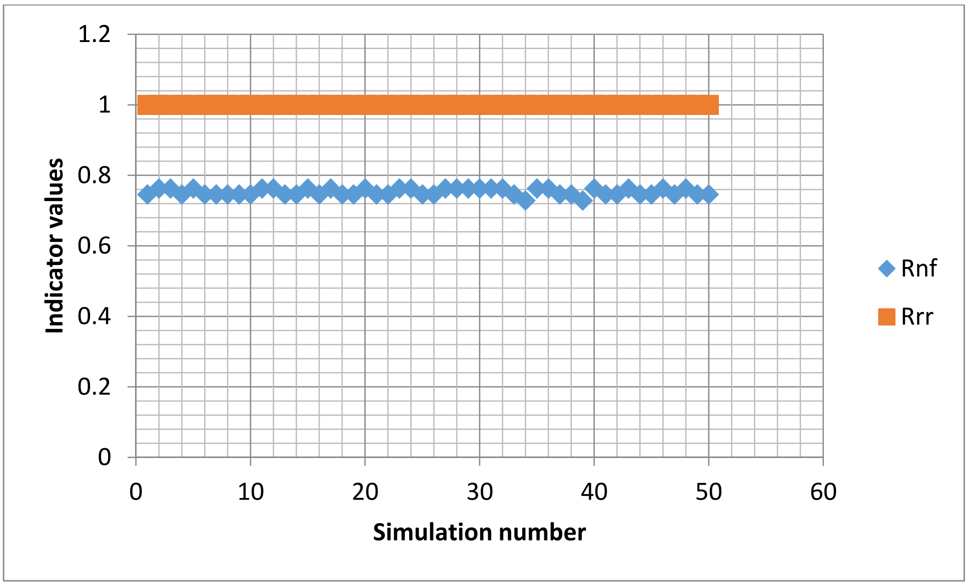


Figure 9.10-non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for twelve month low rainfall period (SEQ Water Grid -0% initial storage)

As seen in Figure 9.10, R_{nf} is approximately 0.76. Compared to the R_{nf} of six months low rainfall period which is 0.8, the non-failure duration has not reduced much for a twelve month low rainfall period. In terms of quantitative recovery of service, the system shows high recoverability.

C: Storage level 50% (six month low rainfall period)

Figure 9.11 shows the worst observed system behaviour obtained from 50 simulations for a six month low rainfall period including the failure threshold (50% storage).

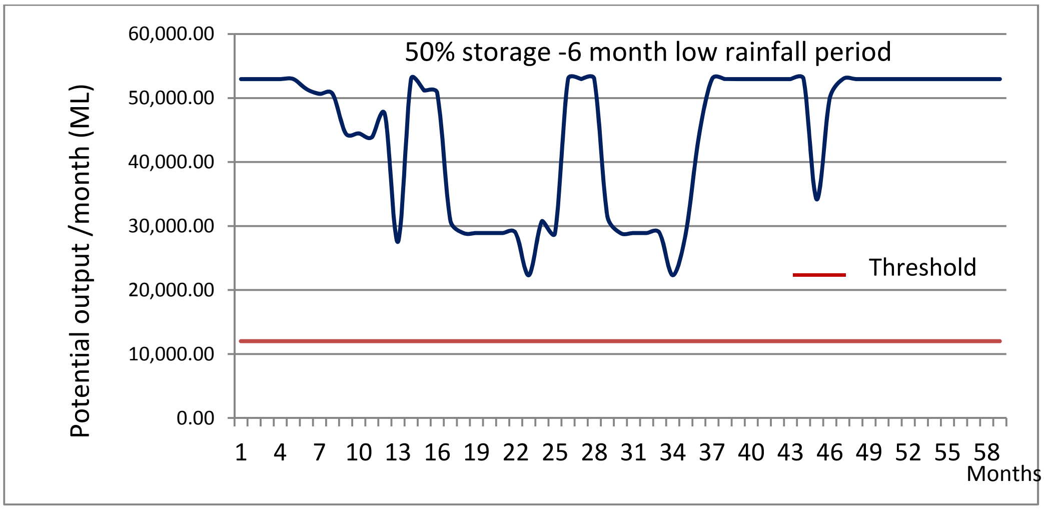


Figure 9.11 – The worst observed system behaviour for six month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 50% initial storage)

As seen in Figure 9.11, the system did not reach the failure state for a six month low rainfall period even in the worst observed behaviour, indicating high ability of the system to withstand a short-term pressure condition. As there is no failure, non-failure ratio and recovery ratio are not relevant in this case.

D: Storage level 50% (twelve month low rainfall period)

Figure 9.12 shows the worst observed system behaviour for a twelve month low rainfall period including the failure threshold obtained from 50 simulations (50% storage).

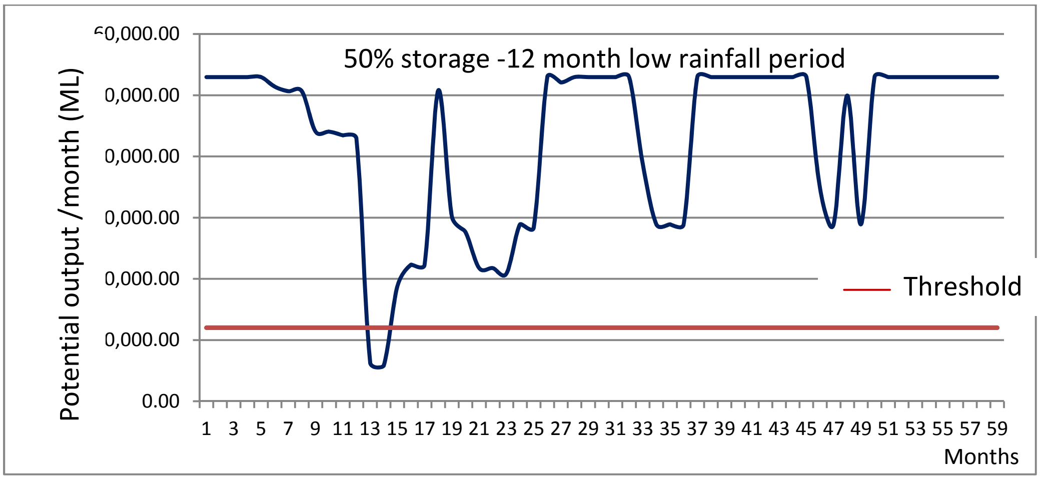


Figure 9.12 – The worst observed system behaviour for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 50% initial storage)

Figure 9.12 shows that for a low rainfall of twelve months (50% storage), the output of the system drops below failure threshold. However, it recovers within a period of two months (mean recovery time 2 months). Therefore, recoverability of the system can be considered as high, for 50% storage. Since the system recovered fully, R_{rr} was 1 for each simulation. R_{nf} and R_{rr} values for each simulation are plotted in the graph given in Figure 9.13.

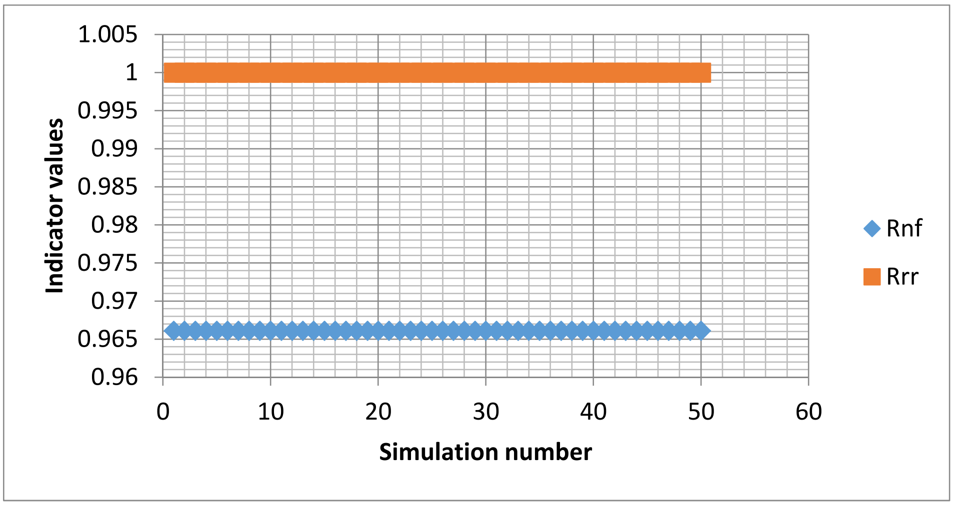


Figure 9.13-Non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for twelve month low rainfall period (SEQ Water Grid -50% initial storage)

Very high non-failure ratio (R_{nf}) around 0.96 (Figure 9.13) indicates that the system does not stay in failure state for a long duration, which is an indication of a highly resilient water supply.

E: Storage level 100% of full capacity

The worst observed system behaviour for a 12 month low rainfall period (100% storage) including failure threshold is illustrated in Figure 9.14.

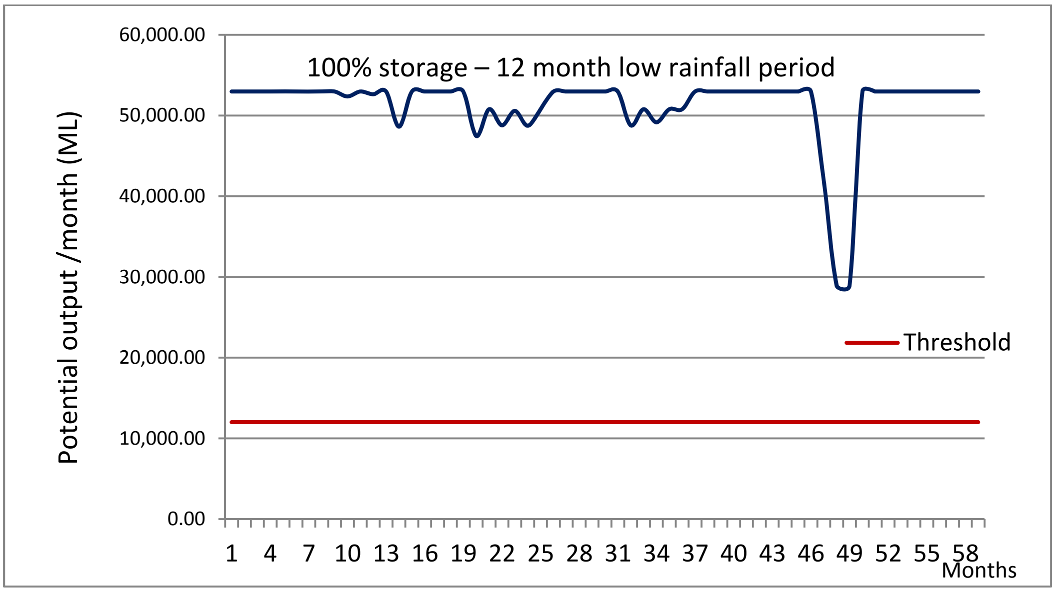


Figure 9.14 – The worst observed system behaviour for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 100% initial storage)

Figure 9.14 shows that the supply has not dropped to the level of failure threshold for 100% storage. Therefore, non-failure ratio and recovery ratio are not relevant in this case.

9.2.4 Interpretation of indicator values of system's ability to recover

Table 9.2 shows that for an extreme storage condition of 0% combined with six month and twelve month low rainfall periods, the system takes considerable period of time for recovery (13 and 17 months, respectively) . However for storage of 50% or above, the system's ability to recover is very high. The system will recover within two months after a twelve month low rainfall period. This fact is justified by the high non-failure ratio of 0.97 indicating that for a twelve month low rainfall period, 97% of the observed duration, the system is capable of maintaining the supply potential above failure threshold. The recovery ratio (R_{rr}) of 1 indicates that after recovery, the system is capable of providing its maximum level of service.

Table 9.2 – System's ability to recover under different storage conditions

Scenario → / Indicator ↓	0% storage		50% storage		100% storage
	6 months low rainfall	12 months low rainfall	6 months low rainfall	12 months low rainfall	12 months low rainfall
Recovery time (months)	13	17	No failure	2	No failure
Non failure ratio	0.80	0.76	N/A	0.97	N/A
Recovery ratio	1	1	N/A	1	N/A

9.3 INTERPRETATION OF RESILIENCE IN TERMS OF PROBABILITY OF FAILURE

This section further illustrates systemic resilience of the water supply system in terms of probability of failure. As explained in Section 4.2.1, the probability of failure was considered as a surrogate measure of resilience in this study. Higher probability of failure under a certain pressure condition indicates low ability to withstand that level of pressure. Based on this definition, the probability of failure of the SEQ Water Grid for different levels of rainfall was investigated. The process of obtaining the probability of failure is explained below.

Firstly, 100 simulations were carried out in order to generate a sample population of 100 from the SEQ Water Grid model for a five year period under average (100%) and reduced (90% , 80% …. 20%) rainfall and storage levels of 0%, 50% and 100%. The reason for considering a five year period was explained in Section 7.3.1. Each simulation gave potential output of the system for 60 months, as the simulation ran for a five year period. The supply level below failure threshold (at least for one month out of 60 months) was considered as one count of failure. Number of failures was obtained from 100 simulations.

Probability of failure was obtained by dividing the number of failures by total number of simulations (100). Probability of failure for each storage level (0%, 50% and 100%) was evaluated for different rainfall reduced levels. The three curves of probability of failure for selected storage levels are shown in Figure 9.15. The reducing rainfall implies increasing pressure. Hence, high probability of failure indicates low resilience, as illustrated in Figure 9.15. In contrast, low probability of failure (for high pressure conditions) indicates high resilience.

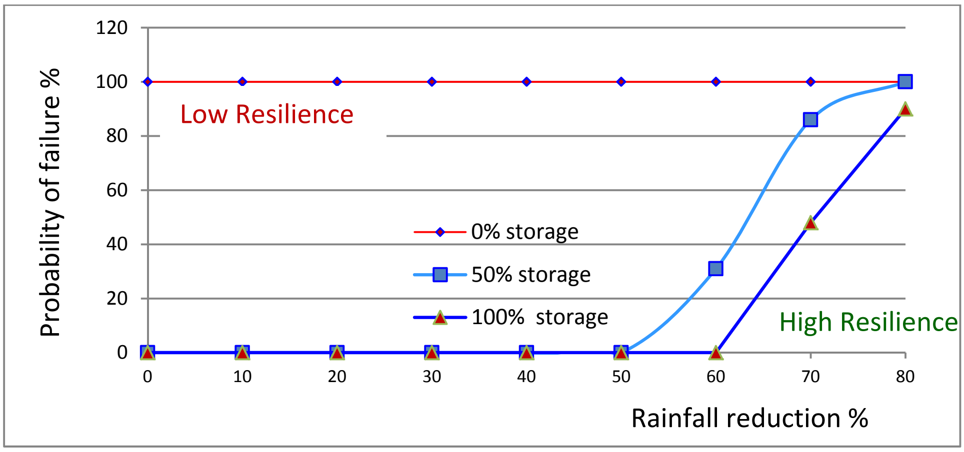


Figure 9.15 – Probability of failure for different storage conditions

The probability of failure curves for initial 0% storage and 100% storage indicate the operational range of the system. For 0% initial storage, during the first few months even for average rainfall without any rainfall reduction, the supply level was below failure threshold, indicating certain failure. Therefore, probability of failure was 100%. As the storage increased, the supply potential of the system increased and the failure probability became zero even under 60% reduced rainfall conditions below average. High systemic resilience was shown even for 50% storage levels. Therefore, the operational range of the SEQ Water Grid, for storage above 50%, lies close to the high resilience region.

The above analysis was carried out considering different possible climatic and storage scenarios. It is useful to evaluate the above results against expected storage conditions predicted by the Queensland Water Commission (2012) in order to understand the status of the SEQ Water Grid.

The storage conditions in the main SEQ Water Grid reservoirs are predicted by the Queensland Water Commission (2012) as given in Table 9.3. According to the predictions, the probability of dropping the storage level of the main SEQ Water Grid sources to 50% within 5 years is even less than 5%.

Table 9.3 – Probability of reaching specified storage levels of main SEQ Water Grid reservoirs over a five year period (adapted from QWC 2012)

(1)	Probability of reaching the storage percentage indicated in column (1) of main SEQ Water Grid reservoirs		
	Within 1 year	Within 3 years	Within 5 years
40% storage	Less than 0.2%	Not specified	Less than 5%
30% storage	Not specified	Less than 0.5%	Less than 1%

As noted by the Queensland Government (2013), the amount of rainfall reduction due to climate change, under high (worst) emission scenarios has been projected as 8% below 1971-2000 historical mean by 2070 as given in Section 6.4. Accordingly, for the SEQ region, the critical climatic conditions for the near future (till 2070) can be expected not to be reached beyond 10% rainfall reduction level below average.

Therefore, although the model simulations carried out in this research project were designed to examine the system status up to 80% reduced rainfall, the most appropriate climate conditions will be 10% reduced rainfall below average. The most likely storage scenario will be above 50% of full capacity storage conditions (as the probability of reaching 50% storage is less than 5%). For these two conditions (10% rainfall reduction and 50% storage), the SEQ Water Grid shows high systemic resilience and therefore the system is expected to function with a high degree of reliability.

9.4 ANALYSIS FOR DEMAND VARIATIONS

The rainfall volume was the main variable considered for all of the above analyses because the evaluation was based on supply potential of the system, irrespective of the demand. However, for further analysis, variation of rainfall as well as demand was taken into account for assessing future conditions. Accordingly, rainfall and demand were considered as two independent variables. The illustration of probability of failure under two independent pressure variables for a generic system is shown in Figure 9.16 in order to define high-low resilience regions, which is adapted to illustrate the probability of failure of water supply system under rainfall and demand variations.

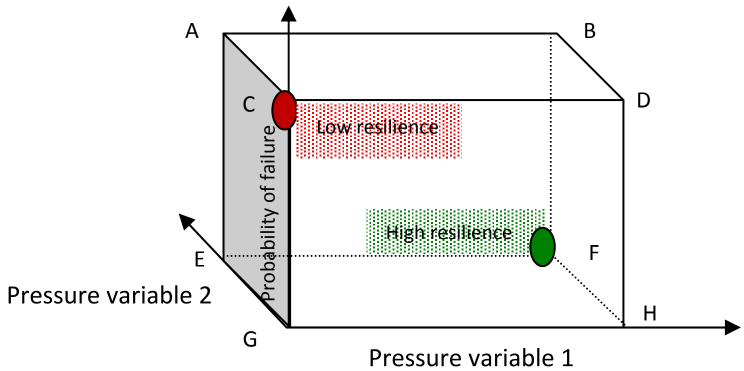


Figure 9.16 - High and low resilience regions with respect to two pressure conditions

The probability of failure of a generic system subject to two pressure variables could be illustrated as shown in Figure 9.16,. The region close to ‘G’ represents the region of lowest pressure, as the pressure 1 increases towards ‘H’ and pressure 2 increases towards ‘E’. The region close to ‘C’ indicates high failure probability even under low pressure conditions. Therefore, the region close to ‘C’ represents the low resilience region. Similarly, the region ‘F’ represents low probability of failure under high pressure conditions indicating the high resilience region.

Considering, decrease in rainfall and increase in demand as the two pressure variables, the three dimensional graphs for 50% and 100% storages for SEQ Water Grid were developed as shown in Figure 9.17 and Figure 9.18 below.

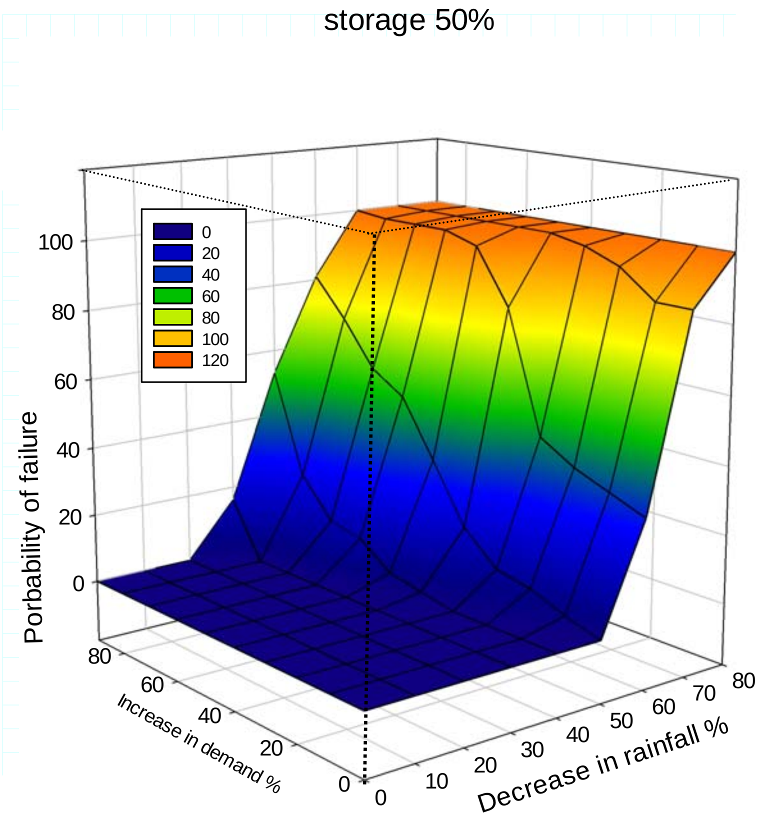


Figure 9.17 - Representation of resilience for 50% storage (simulated results for SEO Water Grid)

Figure 9.17 shows the probability of failure as a dependent variable with the decrease in rainfall and increase in demand for 50% storage. The explanation given in Figure 9.16 for high and low resilience regions was adopted to define the high and low resilience regions in Figure 9.17 The surface indicates the failure probability of the system. The colours show the upper levels of failure probability as indicated by the legend. As the surface is far from the low resilience region for low levels of pressures, the resilience is high for low level of pressures. The reference (0) levels of pressure in this study were the ***average*** rainfall and ***current*** (2010) demand levels (without any decrease in the average rainfall and increase in current demand). However, with the increase in pressures, the surface shifts towards the low resilience region. It can also be noted that the loss of resilience takes place at a very fast rate after reaching a certain level of pressure.

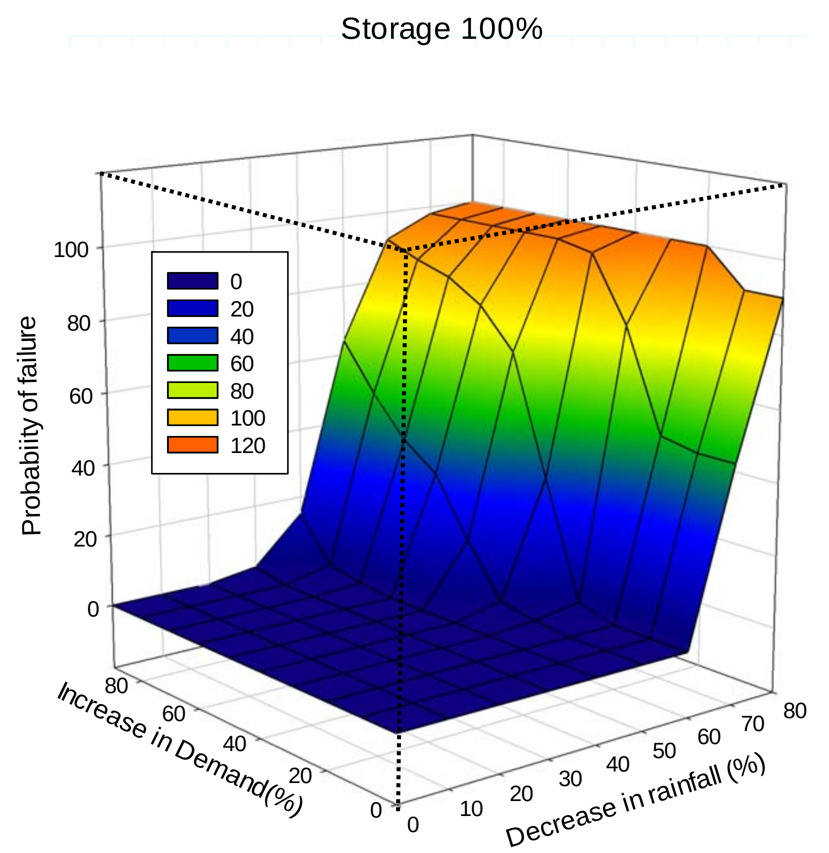


Figure 9.18- Representation of resilience for 100% storage (simulated results for SEQ Water Grid)

Figure 9.18 shows that the system maintains low probability of failure until 60% reduction in rainfall under current demand when storage level is 100%. It also shows that the impact of increase in demand is not very significant.

This knowledge can allow decision makers to formulate early intervention strategies for a predicted long-term low rainfall period. A common approach by water supply authorities is the introduction of water restrictions in order to maintain storage levels for a longer period of time as a precaution in the event of a predicted drought. The failure surface helps to identity the trigger points for early actions such as the introduction of water restrictions. Such mitigation actions are very important to prevent catastrophic failure.

Managerial decisions should be taken at the trigger points. For example, decrease in rainfall below 40% combined with increasing demand shows a major shifting of the surface towards the low resilience region, indicating high rate of resilience loss in the SEQ Water Grid. It is notable that a rapid loss of resilience takes place when rainfall decreases by approximately 50% for 50% storage (under current demand). However, when storage is 100%, loss of resilience commences with 60% decrease in rainfall. Therefore, timely water saving measures such as the introduction of suitable water restrictions for the predicted low rainfall conditions can be appropriately formulated by observing the change points on the surface.

In practice, the key parameter that triggers water restrictions is the reservoir storage level. Therefore, the main criterion for identifying the trigger point for water restrictions is the storage level. In this context, evaluation of the relationship of failure probability to the storage levels is very useful. Figure 9.17 and Figure 9.18 illustrated the failure probability considering only two storage conditions; 50% and 100%. However, it is necessary to evaluate the probability of failure for different storage levels for decision making. Figure 9.19, illustrates the relationship of failure probability for different storage levels and different rainfall conditions for current demand.

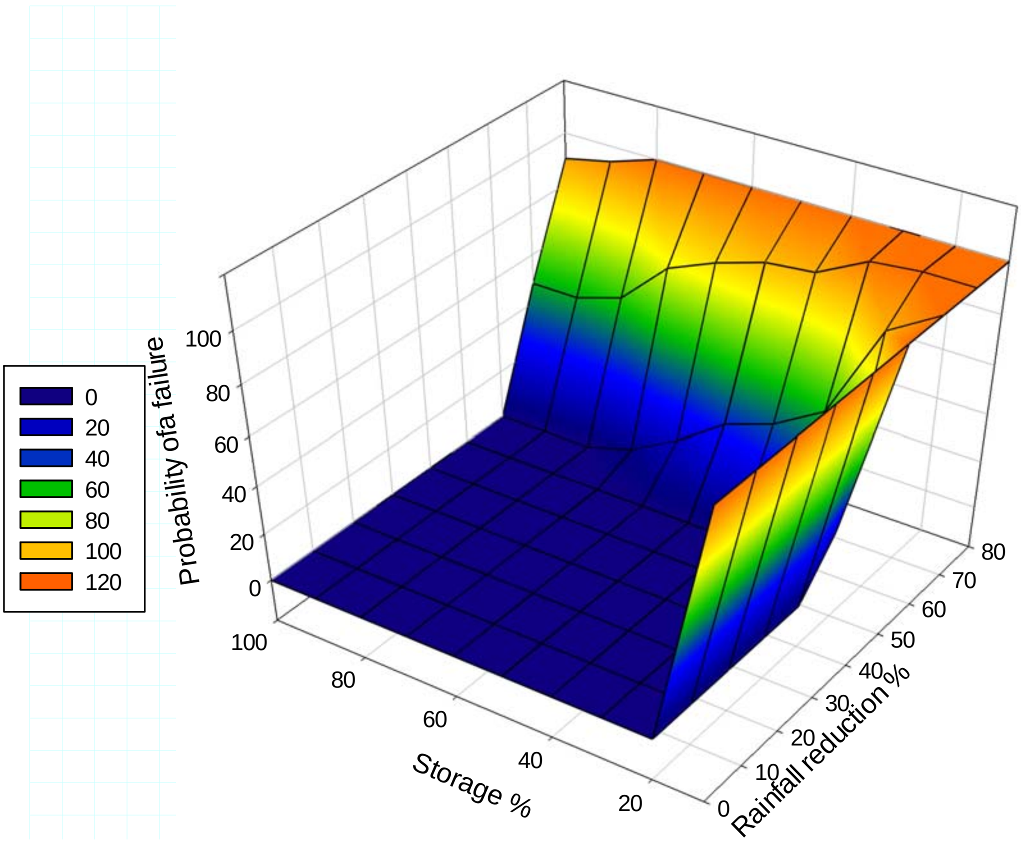


Figure 9.19 – Probability of failure under different storage and rainfall conditions (simulated results for SEO Water Grid)

The SEQ Water Grid has very low probability of failure until the storage drops to approximately 20% of the full capacity level. Figure 9.20 visualises clearly the failure probabilities with respect to storage and rainfall reduced levels in a two-dimensional space. The legend indicates the upper limits of failure probabilities assigned to each colour.

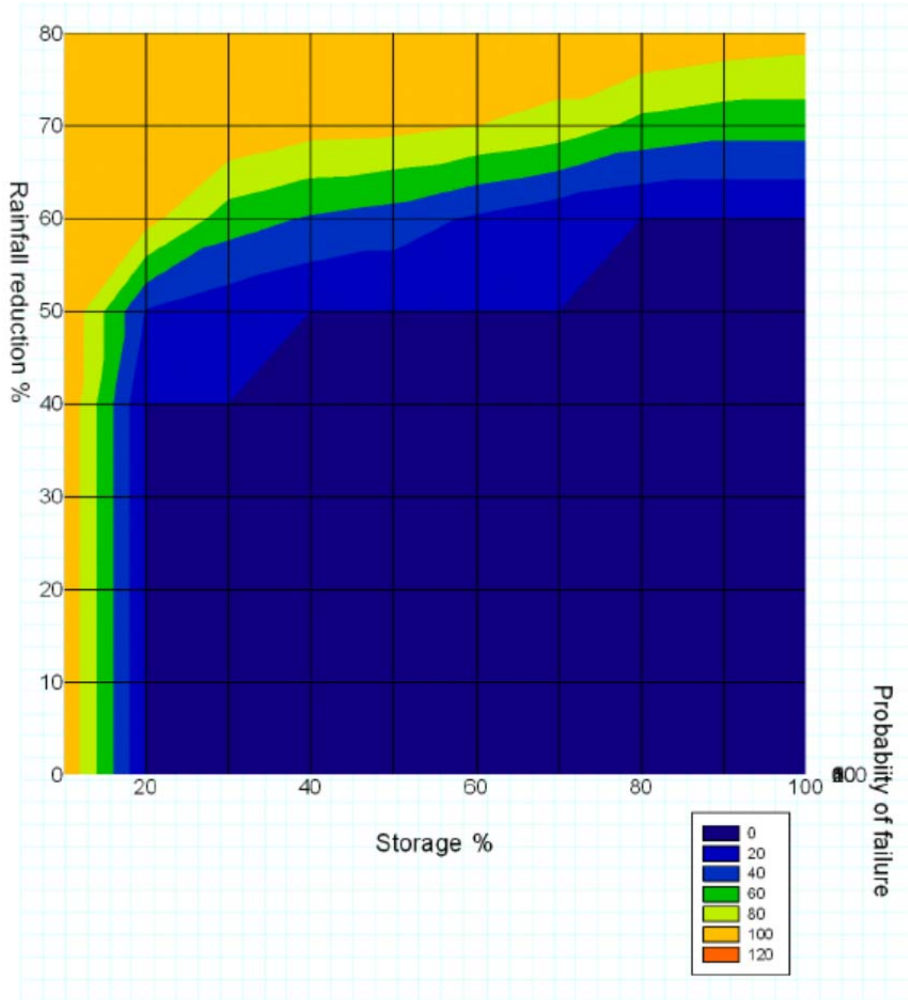


Figure 9.20- Illustrations of failure probabilities in a two-dimensional plane with respect to different storage and rainfall conditions for current demand (simulated results for SEQ Water Grid)

Figure 9.20 shows that under average rainfall (0% rainfall reduction) and current demand conditions, probability of failure is very low until the storage levels drop to 20% capacity. Below 20% storage, the probability of failure increases rapidly.

Therefore, water restriction measures should be introduced before reaching the critical storage levels.

Water restriction is a measure of preserving storage with a view to using the available water for a longer period. These restrictions are initially enforced with a low level of restrictions, which prevent non-urgent water usage (for example, external uses such as sprinklers), and advance into higher restriction levels as the storage drops further.

Figure 9.21 below shows the SEQ household water usage as noted by the Department of Energy and Water Supply (2013). It shows that 4% of household water is used for irrigation. Therefore, by restricting outdoor water usages (for irrigation), at least 4% of water usage can be saved from initial restrictions

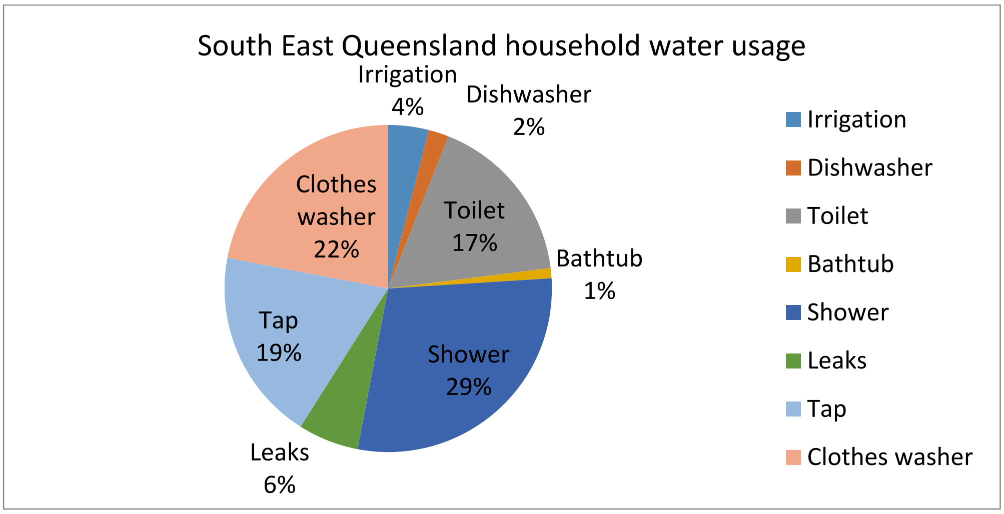


Figure 9.21 – South East Queensland household water usage (adapted from Department of Energy and Water supply (2013)

However, 4% water savings does not show significant improvement in storage conditions as shown in Figure 9.22 below. Compared to Figure 9.20, the difference in Figure 9.22 is almost negligible. It indicates that by restricting only outdoor water usage, the SEQ Water Grid does not achieve enhanced resilience of the system.

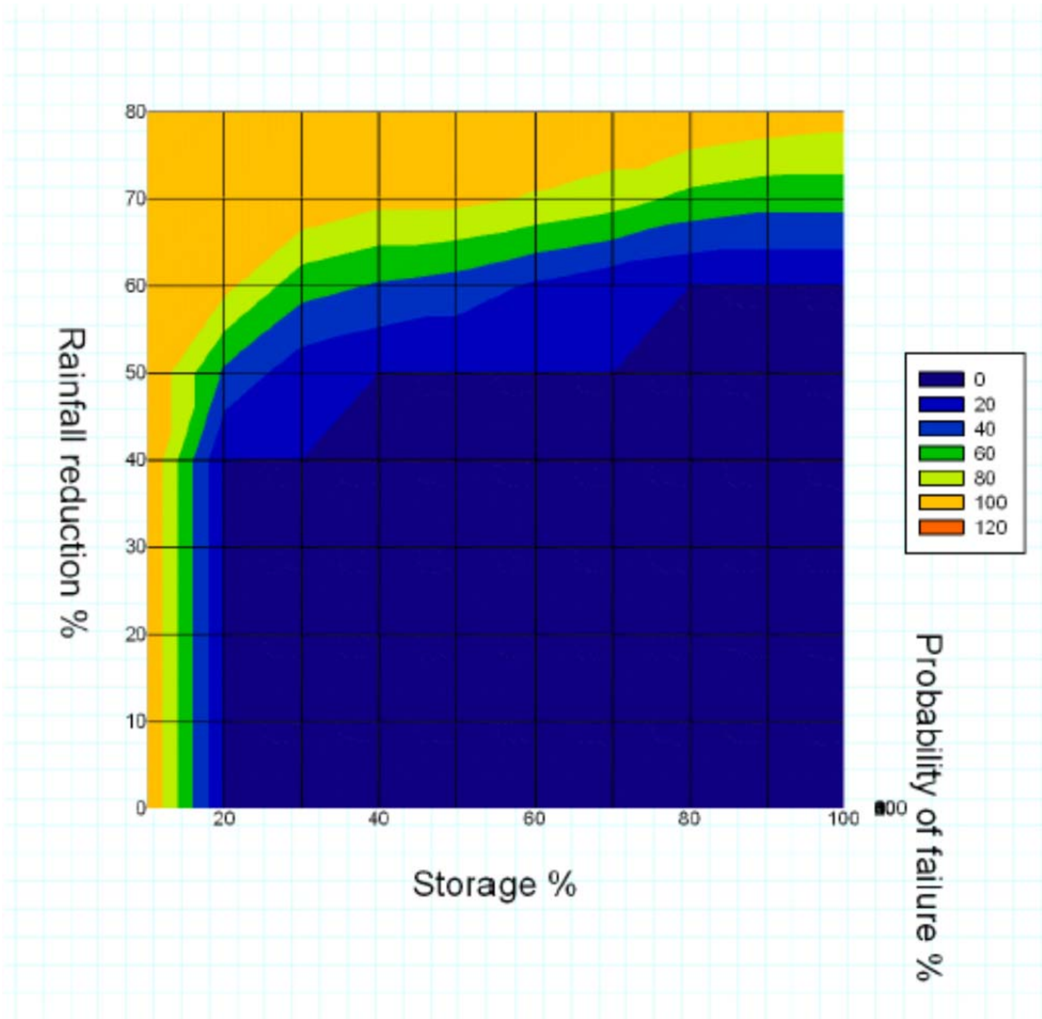


Figure 9.22- Probability of failure of SEQ Water Grid for 4% water savings (simulated results for SEQ Water Grid)

Therefore, for the SEQ Water Grid, restrictions might be applied when the storage level drops to approximately 40% capacity level as a precautionary measure. As the storage drops further, higher level of restrictions need to be applied. Therefore, under current conditions, the trigger point for introducing water restrictions for the SEQ Water Grid can be identified as 40% storage level.

9.5 PREDICTIONS FOR DIFFERENT RAINFALL, STORAGE AND DEMAND CONDITIONS

In order to obtain data sets for different scenarios based on simulated results, a large number of simulations should be carried out to determine the probability of failure under each scenario. As a method for evaluating the probability of failure under different variables without using a large number of model simulations for each scenario, logistic regression can be used. Accordingly, for predicting the probability of failure under different rainfall, demand and storage conditions, a logistic regression model was used as explained below.

In binary logistic regression, for independent variables X_1, X_2, ...X_k, the dependent variable D can be either an event which takes place successfully or not. Successful occurrence of an event should be pre-defined. Accordingly, for independent variables X_1, X_2, ...X_k, the occurrence of failure representing 1 and non-failure representing 0 can be denoted as:

$$X_1, X_2, \ldots X_k \Longrightarrow D\,(1,0) \begin{cases} \text{Failure} & 1 \\ \text{Non-Failure} & 0 \end{cases}$$

The logistic model is defined as;

$$\mathbf{P}\,(D=1 / X_1, X2,..\, X_k\,) = \frac{1}{1+e-(\beta 0+\beta 1x1+\beta 2x2.....\beta nxn)} \quad .... \textit{Equation 9.1}$$

Where $P(D=1 / X_1, X_2.. X_k)$ is the conditional probability of failure which occurs under dependent variable conditions specified by X_1, X_2,.... X_k . and β_0, β_1 ... β_n, parameters. Considering X_1, X_2 and X_3 as the rainfall, demand and the storage, respectively, the above equation can be written as;

$$P\,(x) = \frac{1}{1+e-(\beta 0+\beta 1\ Rainfall+\beta 2\ Demand+\beta 3\ Storage)} \quad .... \textit{Equation 9.2}$$

Using the STELLA model, a data set for four different levels of each independent variable was generated in order to determine the parameters β_0, β_1 β_2, β_3. The selection of four levels of each variable is explained below.

The critical issue for rainfall and storage are the decreasing trend and for demand is the increasing trend. Accordingly, four different levels of each variable were considered as: for rainfall, 100%, 75%, 50%, 25%; for storage 100%, 75%, 50%, 25%; and for demand 100%, 125%, 150%, 200%. The data set is given in Table 9.4. Using SPSS software and the data set, the parameters β_0, β_1, β_2 and β_3 were obtained which are given in Table 9.5.

Table 9.4- Probability of failure from STELLA model simulations for SEQ Water Grid

No of simulations	failure months	No of sim. With failure months (count)	Rainfall %	Demand %	Storage %	Probability of failure = Count /No of sim.	Failure below 50% =0, above 50% =1
50	0	0	100	100	100	0	0
50	0	0	100	100	75	0	0
50	0	0	100	100	50	0	0
50	0	0	100	100	25	0	0
50	0	0	100	125	100	0	0
50	0	0	100	125	75	0	0
50	0	0	100	125	50	0	0
50	1	1	100	125	25	0.02	0
50	0	0	100	150	100	0	0
50	0	0	100	150	75	0	0
50	0	0	100	150	50	0	0
50	5	4	100	150	25	0.08	0
50	0	0	100	200	100	0	0
50	0	0	100	200	75	0	0
50	0	0	100	200	50	0	0
50	24	17	100	200	25	0.34	0
50	0	0	75	100	100	0	0
50	0	0	75	100	75	0	0
50	0	0	75	100	50	0	0
50	53	50	75	100	25	1	1
50	0	0	75	125	100	0	0

Table 9.4 continued

No of simulations	failure months	No of sim. With failure months (count)	Rainfall %	Demand %	Storage %	Probability of failure = Count /No of sim.	Failure below 50% =0, above 50% =1
50	0	0	75	125	75	0	0
50	0	0	75	125	50	0	0
50	111	50	75	125	25	1	1
50	0	0	75	150	100	0	0
50	0	0	75	150	75	0	0
50	0	0	75	150	50	0	0
50	119	50	75	150	25	1	1
50	0	0	75	200	100	0	0
50	0	0	75	200	75	0	0
50	0	0	75	200	50	0	0
50	198	50	75	200	25	1	1
50	0	0	50	100	100	0	0
50	0	0	50	100	75	0	0
50	2	1	50	100	50	0.02	0
50	21	12	50	100	25	0.24	0
50	0	0	50	125	100	0	0
50	0	0	50	125	75	0	0
50	2	1	50	125	50	0.02	0
50	52	17	50	125	25	0.34	0
50	25	15	50	150	100	0.3	0
50	44	21	50	150	75	0.42	0
50	51	24	50	150	50	0.48	0
50	189	44	50	150	25	0.88	1
50	187	31	50	200	100	0.62	1
50	250	38	50	200	75	0.76	1
50	404	47	50	200	50	0.94	1
50	845	50	50	200	25	1	1
50	263	35	25	100	100	0.7	1
50	506	49	25	100	75	0.98	1
50	823	49	25	100	50	0.98	1
50	1183	50	25	100	25	1	1
50	407	47	25	125	100	0.94	1
50	704	50	25	125	75	1	1
50	1112	50	25	125	50	1	1
50	1627	50	25	125	25	1	1
50	927	50	25	150	100	1	1
50	1119	50	25	150	75	1	1

Table 9.4 continued

No of simulations	failure months	No of sim. With failure months (count)	Rainfall %	Demand %	Storage %	Probability of failure = Count /No of sim.	Failure below 50% =0, above 50% =1
50	1662	50	25	150	50	1	1
50	2178	50	25	150	25	1	1
50	1221	50	25	200	100	1	1
50	1755	50	25	200	75	1	1
50	2043	50	25	200	50	1	1
50	2621	50	25	200	25	1	1

Table 9.5 – SPSS output data indicating parameter values

	Parameter values (Standard Error)
Constant (β_0)	4.453 (2.345)
Rainfall (β_1)	-0.121 (0.032)
Demand (β_2)	0.033 (0.014)
Storage (β_3)	-0.046 (0.019)

By substituting β_0= 4.453, β_1= -0.121, β_2 = 0.033 and β_3= -0.046 in Equation 9.2, for any variable conditions of rainfall and storage, the probability of failure can be obtained. This can be used to evaluate the status of the system in terms of probability of failure for future climate predictions.

9.6 MODEL VALIDATION

A measure of goodness-of-fit of a logistic regression model can be evaluated by a receiver operating characteristic (ROC) curve. SPSS was used in to derive the ROC for this study and determine the area under the curve. The area under an ROC can range between 0.5 and 1.0 with larger values indicative of better fit. The ROC curve of the logistic regression model used in this study is given in Figure 9.23 and the area under curve was given as 0.939 indicating the goodness-of-fit of the model.

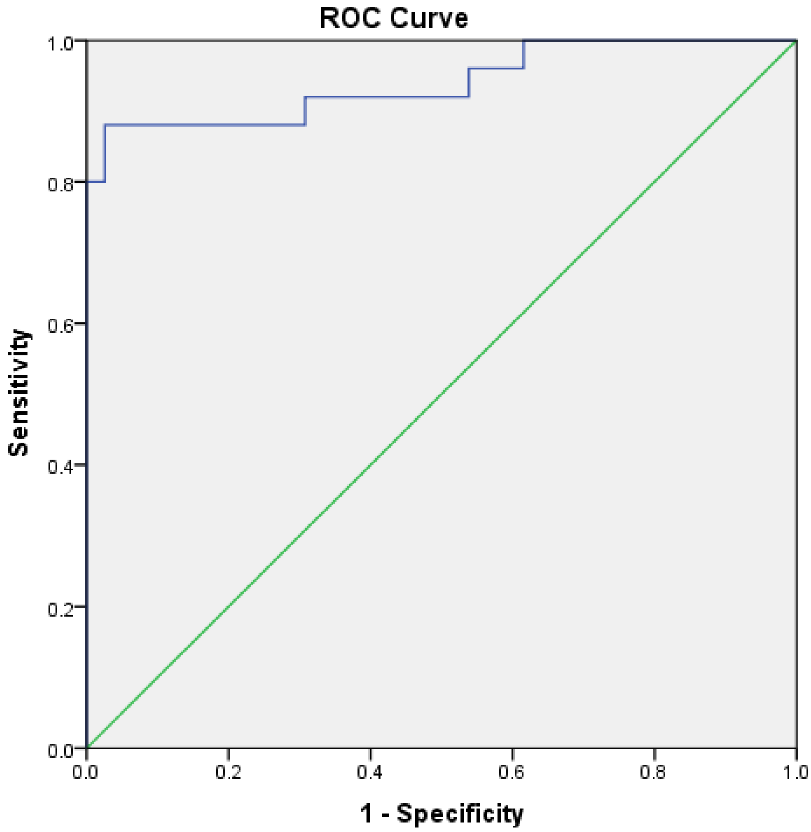


Figure 9.23- ROC Curve for the logistic regression model

For validation of the model, a data set was generated from the STELLA model for combinations of different rainfall (20%, 40%, 60%, 80% of average), demand (120%, 140%, 160%, 180% of current demand) and storage (20%, 40%, 60%, 80% of storage) and compared with the predicted output as given in Figure 9.24.

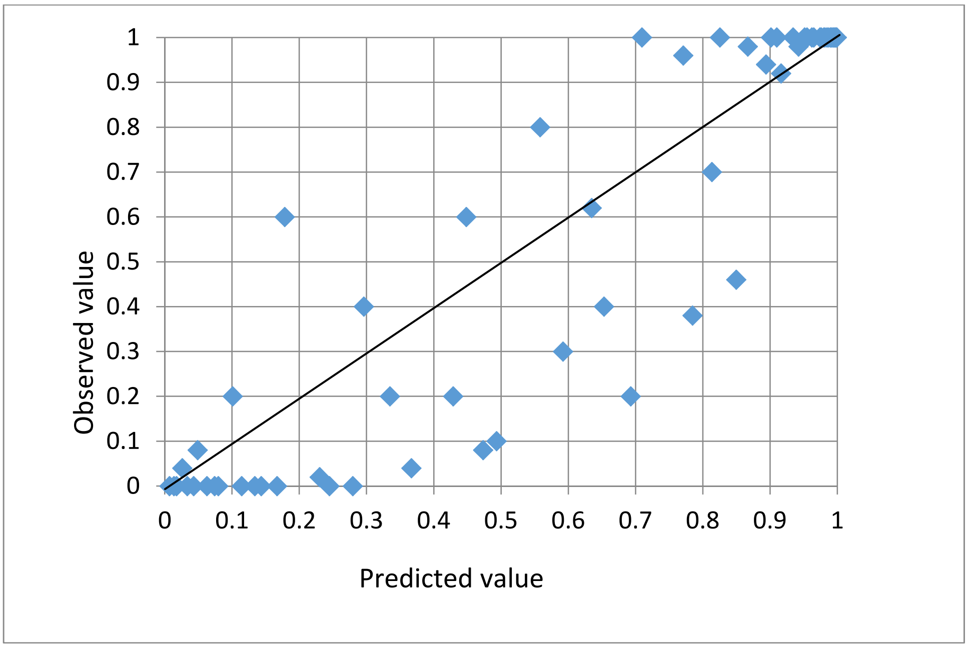


Figure 9.24- Predicted values vs observed values graph of the logistic regression model

Figure 9.24 shows that the predicted values have deviated from observed values, especially when the probability of failure is not 0 or 100%. As the observed values were obtained from STELLA model which has been developed as a stochastic model, different output is generated for the same input for different simulations. Therefore, the observed value might differ from the predicted value as shown in Figure 9.24. However, Figure 9.24 shows a reasonable accuracy in predictability of the regression model.

9.7 CONCLUSIONS

This Chapter set out to investigate the application of approach for Resilience Assessment developed in earlier chapters to a real case study. The SEQ Water Grid was used as a case study and the systemic resilience was evaluated by examining the system behaviour using model simulation results. The main characteristics evaluated were the ability of the system to withstand pressure and the ability to recover. These two characteristics help to maintain satisfactory level of service delivery of the system.

According to the predictions, rainfall in SEQ region is expected to reduce by approximately 8% by 2070 under a high emission scenario. It has also been predicted that the probability of dropping the SEQ storages to 40% level within the next five years is less than 5%. The analysis indicates that the SEQ Water Grid shows high resilience, even with 40% reduction in rainfall for 50% storage conditions. For higher storage conditions, resilience is even higher. As the SEQ Water Grid has a large storage capacity, it has the ability to recover from failure state within a short period. Therefore, the SEQ Water Grid is expected to perform as a high resilience system under the impacts of climate change and increasing demand. It was also identified that loss of systemic resilience takes place at a faster rate as rainfall, demand and storage become unfavourable. The trigger point for introducing the first level of water restrictions for the SEQ Water Grid should be when the storage levels reach approximately 40% of the capacity level.

Considering demand, rainfall and storage as the main variables, parameter values for each variable were obtained for predicting probability of failure under future climate and demand conditions. These parameter values can be used in a Logistic Regression model. By evaluating the probability of failure under future climate conditions, demand and storage conditions, resilience of the system under these specific conditions can be determined.

Depending on the storage capacity and demand conditions, different systems show different degrees of resilience for the same percentage levels of storage. However, the important aspect of the analysis is that the procedure introduced for a resilience assessment of a water supply system can be applied for a generic water supply system for assessing systemic resilience to different types of pressures.

Chapter 10: Conclusions and Recommendations for Further Research

10.1 CONCLUSIONS

Development of approaches to evaluate infrastructure resilience contributes to enhancing decision making in infrastructure management. The main outcome of this research was the development of an objective approach for assessing resilience of a water supply system to two types of pre-defined pressure. The two pre-defined pressures considered were the reducing trend of rainfall due to climate change and increasing trends of demand due to population growth.

Climate change involves uncertainty in weather predictions. Therefore, system operators may find it difficult to maintain the consistency of supply due to pressures caused by consequences of climate change. The demand increase due to population growth is an additional pressure on the system. The knowledge of systemic resilience to these pressures helps to avoid catastrophic failures of the system.

In many previous resilience assessment studies, different components of a water supply system had been considered separately. Combining the outcomes of such assessments might not reflect the overall resilience for the entire system. This is due to the possibility of depreciation of high resilience in one subsystem by the low resilience of another subsystem. Therefore, as a more realistic approach, the meta-system concept was introduced to consider an integrated system instead of considering different components of the system separately. In this approach, a water supply system which belongs to ecological-technical and social subsystems was considered as a single meta-system. Defining the important requirements for resilience assessment, such as operational resilience characteristics of the system and failure criteria were important steps towards developing the resilience assessment process, which was carried out in this study.

The development of a practical method for evaluating resilience of a water supply system was a result of a step-wise procedure. Hence, the numerical values used in this study are for illustration purposes only.

The important processes identified and explored in this study for developing the resilience assessment approach and the outcome are listed below.

- *Identification of the operational resilience characteristics of a water supply system*

The primary objective of a water supply system is to supply potable water of an adequate quantity to the consumers. Therefore, a resilient system should have the ability to maintain services with least service failures. That can occur when the system has the ability to withstand pressure and has the ability to recover rapidly after a failure event. Hence, the attributes that contribute to enhance those requirements were considered as the operational resilience characteristics. The following factors were identified as contributors to enhance the resilience of a water supply system, considering the water supply system in entirety:

  - Available Storage
  - Climate elasticity of stream flow to the catchment
  - Capacity to treat low quality water
  - Connectivity to multiple treatment plants
  - Alternative supply sources
  - System management procedures.

- *Evaluation of the relationship of resilience characteristics and pressures to identify suitable indicators to express systemic resilience*

In order to quantify the ability of the system to withstand pre-defined pressures (identified as climate change and population growth impacts) and ability to recover as a way of expressing resilience, the relationship between the above-mentioned pressures and the resilience characteristics were evaluated. The relationship identified the parameters that indicate the variations in system behaviour when subjected to pressure. The indicators, design pressure to threshold pressure ratio (R_{pp}), service reduction ratio (R_{ss}), service reduction rate **(**R_{sp}), non-failure ratio **(**R_{nf}) and recovery ratio ***(***R_{rr}), were proposed as suitable indicators for expressing systemic resilience. These indicators show how much additional pressure can be absorbed by the system before reaching the threshold pressure limit. For example, the case study, the SEQ Water Grid had R_{pp} value of 0.4 for 50% storage indicating that the system has the capacity for operating approximately 0.4 times above average pressure of low rainfall (0.4 times below average rainfall conditions) without failure. For 100% storage, the R_{pp} value was as high as 0.6. Service reduction ratio (R_{ss}) of 0.31 (for 50% storage) indicates that the SEQ Water Grid has the capacity to operate without failure until the service potential drops up to 31% of the full supply capacity at the threshold pressure. For 100% storage, R_{ss} value was 0.28. Having knowledge of these indicator values, the system operators are able to react appropriately for predicted pressures. Accordingly, the SEQ Water Grid is expected to operate as a high resilience system providing reliable supply under the pressure of climate change and population growth impacts.

- *Defining a failure threshold and interpretation of resilience by evaluating output level against failure threshold*

For expressing performance capability of a water supply system, a failure threshold had to be defined. The failure of a water supply system might be defined considering different factors. As a step forward for developing the resilience assessment, a suitable failure threshold was defined for the selected water supply system in this study as a benchmark for evaluating the output potential. The failure threshold enabled determination of the system state to ascertain if the system was at failure state or not. For example, in the case study, SEQ Water Grid reached the failure state when the rainfall was reduced by 40% below average for 50% storage and 60% below average for 100% storage. A similar approach can be adopted for defining a failure threshold to suit a different infrastructure system in a similar study.

- *Introduction of a surrogate measure of resilience for a water supply system*

As a direct measurement does not exist for expressing resilience, a ‘surrogate measure’ of resilience was required for this purpose. Identification of a suitable surrogate measure involved careful evaluation of various techniques that express system resilience characteristics in quantitative form. Introduction of a suitable surrogate measure for expressing resilience of a water supply system is a step forward in the development of a resilience assessment framework. The probability of failure was proposed as a surrogate measure for expressing resilience of a water supply system. The probability of failure for the case study, SEQ Water Grid, with respect to rainfall variations was 0 for storage levels above 50% until the rainfall was reduced to 50% below average. That was an indication of a high resilience system.

- *Interpretation of resilience related to high and low resilience regions in a three dimensional space, which allows identification of the trigger points for early actions*

As an outcome of this study, a way of expressing resilience was introduced in a three-dimensional space, using the probability of failure as a surrogate measure of resilience. In a three-dimensional plot, the probability of failure against two independent pressures was expressed as a surface. This surface shows the limiting conditions of systemic resilience. The variations or shifting of the surface from high to low resilience regions explain how fast the system could change from high to low resilience. Observations of the variations of the surface help to identify the trigger points. In a water supply system, the trigger points indicate the need for management intervention such as water restrictions as a precautionary measure. For example, the surface of probability of failure, with respect to the decrease in rainfall and increase in demand, shifted from the high resilience region to the low resilience region at a faster rate when the rainfall was reduced by 40% (for 50% storage). That means, the system needs precautionary actions when the rainfall reduces to 40% below average and the storage becomes 50%. The importance of this method is that resilience of any infrastructure system to two types of pressures can be expressed using the same methodology.

10.2 PRACTICAL VALUE OF THE RESEARCH OUTCOMES

The nature of the resilience concept is such that it is difficult to express as a single characteristic/property. It is a combination of similar and overlapped attributes. In the absence of an accepted methodology to assess resilience, it is a challenging task to interpret a parameter to express resilience. The value of the study includes the introduction of a methodology for assessing resilience of a water supply system which helps to understand the dynamic nature of the system and the adaptability to a changing environment, so that the operators of the system are knowledgeable about the maximum pressure levels below which the system can operate. The evaluation of assessment results obtained by the knowledge created in this study allows prevention of catastrophic failure of the system by identifying trigger points for early actions. The practical way of enforcing water restrictions is related to the storage levels. Therefore, relating the trigger points to the storage levels of reservoirs, the operators will be able to formulate the most appropriate water restriction levels, if necessary.

Furthermore, the process introduced in this study can be applied for other infrastructure systems. However, the systemic and climatic conditions that are applicable to different systems might vary. Accordingly, the test scenarios for different systems might differ. However, the same generic methodology can be applied for different systems provided that the services of the system are measurable and a failure criterion is defined.

10.3 RECOMMENDATIONS FOR FURTHER RESEARCH

This research was carried out with a view to introducing a methodology for assessing the resilience of a water supply system to climate change and population growth impacts. For further development of knowledge in this area, the following recommendations are proposed for further research:

- Since rainfall was the main climate parameter that influences the water supply process, changes to rainfall volume were considered to replicate climate change. However, as climate change influences other parameters such as temperature and evaporation, it is recommended to include variations of these parameters in further research. Also, the inclusion of seasonal variations in the analysis is recommended for more accurate outcomes.

- Degradation of water quality due to climate change is an issue of concern in a resilience-related study because the degree of water quality deterioration influences the level of resilience of the system. Therefore, the water quality issue should also be addressed in research that evaluates resilience of water supply systems. However, a detailed data analysis is required to assess the relationships between the degree of water quality deterioration and factors such as rainfall intensity and antecedent dry period, because they are influential factors in runoff generation. Therefore, the development of relationships between water quality degradation and climate change should be undertaken. This would enable water quality issue to be directly addressed using the derived relationships.

- Although the end users are a part of the water supply system, social behaviour was not a focus of this study. Water consumption patterns can vary according to climate change and such variations in consumption affect the resilience of the water supply system. Therefore, social behavioural changes are also a part of the climate change impacts. Accordingly, social behaviour merits further research.

- An in-depth hydrologic study at catchment level was not within the scope of this study, and a preliminary assessment of system behaviour was considered appropriate to determine the system characteristics. Therefore, a system dynamics modelling software was used to model an existing water supply system for evaluation of the system behaviour in this study. However, if a hydraulic model was used for modelling at the catchment scale, the accuracy of the hydraulic process at catchment level would have been more accurately replicated. Therefore, the use of a hydraulic model for the initial part at the catchment scale and linking to a system dynamics model should be considered in a future study in order to further refine the methodology developed.

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<u>Appendix A</u>

SEQ Water Grid Model

The complete SEQ Water Grid model was developed by combining all the stock-and-flow diagrams of catchment/reservoir/treatment plant subsystems. The complete model and the relationships for entering data in the form of equations are given below.

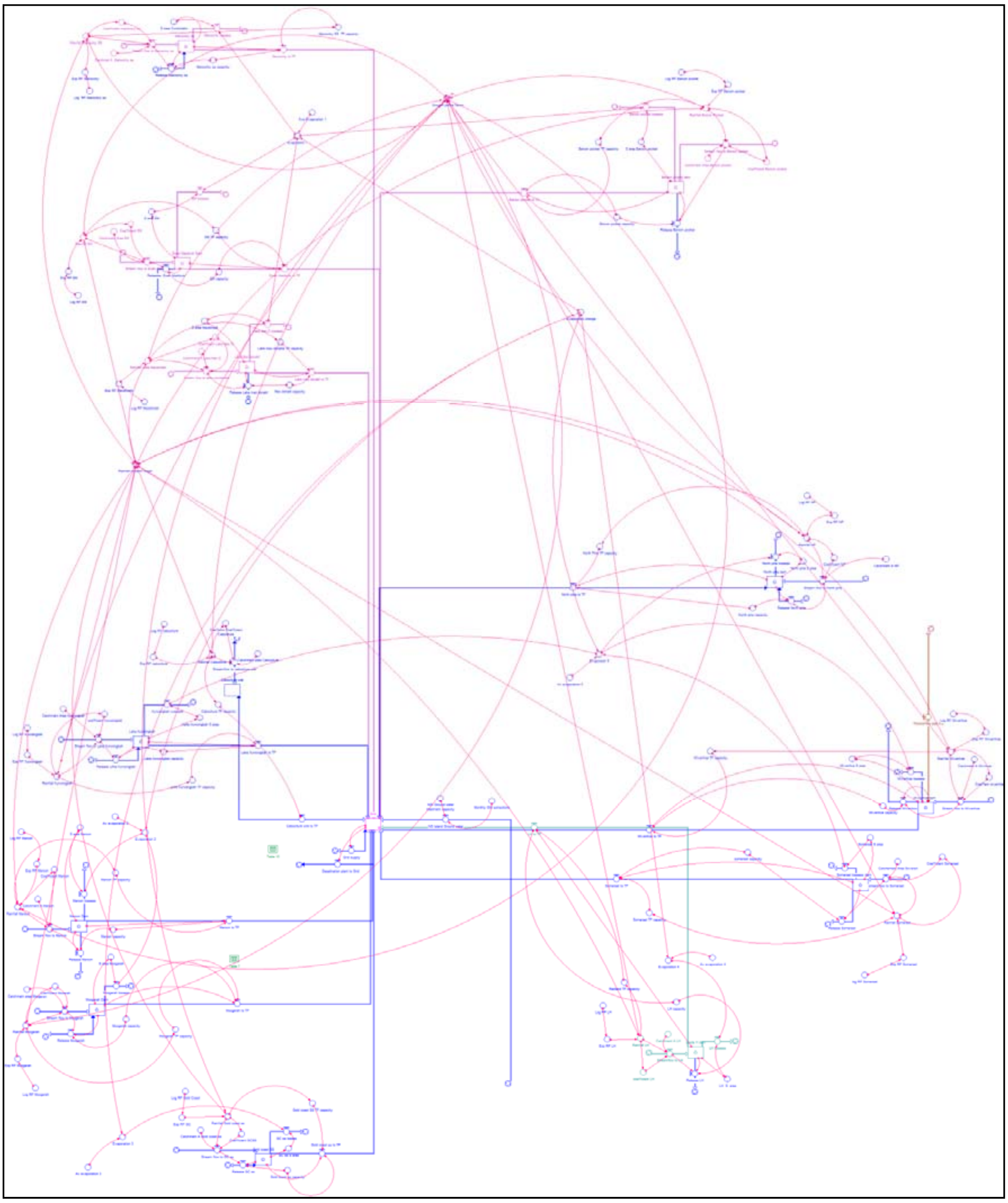

Figure A.1 – SEQ Water Grid model developed in STELLA software

The inflows and outflow for each stock, the conditional relationships of input parameters in the form of equations of the SEQ Water Grid (STELLA model) are given below.

- Grid(t) = Grid(t - dt) + (Desalination_plant_to_Grid + Somerset_to_TP + Wivenhoe_to_TP + North_pine_to_TP + Caboolture_wire_to_TP + Lake_Kurwongbah_to_TP + Moogerah_to_TP + Maroon_to_TP + Gold_coast_ss_to_TP + NS_Island_Ground_water + LH_to_TP + Maroochy_to_TP + Lake_mac_donald_to_TP + Ewen_Maddock_to_TP + Baroon_pocket_to_TP - Grid_supply) * dt
- INIT Grid = 52973

INFLOWS:

- Desalination_plant_to_Grid = If Grid <52973 then 3750 else 0
- Somerset_to_TP = IF Somerset_dam < somerset_capacity*0.2 Then 0 Else Somerset_TP_capacity
- Wivenhoe_to_TP = IF Wivenhoe_dam < Wivenhoe_capacity * 0.2 Then 0 Else Wivenhoe_TP_capacity
- North_pine_to_TP = IF North_pine_dam < 0.2*North_pine_capacity THEN 0 Else North_Pine_TP_capacity
- Caboolture_wire_to_TP = Caboolture_TP_capacity
- Lake_Kurwongbah_to_TP = IF Lake_Kurwongbah <Lake_Kurwongbah_capacity*.2 Then 0 Else Lake_Kurwangbah_TP_capacity
- Moogerah_to_TP = If Moogerah_Dam< 0.2*Moogerah_capacity Then 0 Else Moogerah_TP_capacity
- Maroon_to_TP = IF Maroon_Dam <0.2*Maroon_capacity Then 0 Else Maroon_TP_capacity
- Gold_coast_ss_to_TP = IF Gold_coast_SS < Gold_coast_ss_capacity*0.2 THEN 0 ELSE Gold_coast_SS_TP_capacity
- NS_Island_Ground_water = If Monthly_GW_extractions <NSI_Ground_water_treatmetn_capacity Then Monthly_GW_extractions else NSI_Ground_water_treatmetn_capacity
- LH_to_TP = IF Lesile_H_dam <0.2*LH_capacity THEN 0 ELSE Redland_TP_capaicty
- Maroochy_to_TP = IF Maroochy_ss<Maroochy_ss_capacity*0.2 Then 0 Else Maroochy_SS__TP_capacity
- Lake_mac_donald_to_TP = IF Lake_Mac_donald < Mac_donald_capacity* 0.2 Then 0 Else Lake_mac_donalds_TP_capacity
- Ewen_Maddock_to_TP = IF Ewen_Maddock_Dam< EM_capacity*0.2 Then 0 Else EM_TP_capactiy
- Baroon_pocket_to_TP = IF Baroon_pocket_dam < Baroon_pocket_capacity *0.2 Then 0 Else Baroon_pocket_TP_capacity

OUTFLOWS:

- Grid_supply = If Grid<0 or Grid=0 then 0 else if Grid>52973 then 52973 else if Grid > 0 or Grid < 52973 then Grid else 1000
- Baroon_pocket_dam(t) = Baroon_pocket_dam(t - dt) + (Stream_flow_to_Baroon_pocket - Baroon_pocket_to_TP - Baroon_pocket_lossess - Release_Baroon_pocket) * dt
- INIT Baroon_pocket_dam = 61000

INFLOWS:

- Stream_flow_to_Baroon_pocket = Catchmetn_Area_Baroon_pocket*Coefficient_Baroon_pocket*Rainfall_Baroon_Pocket

OUTFLOWS:

- Baroon_pocket_to_TP = IF Baroon_pocket_dam < Baroon_pocket_capacity *0.2 Then 0 Else Baroon_pocket_TP_capacity
- Baroon_pocket_lossess = evaporation_1*0.75*S_area_Baroon_pocket
- Release_Baroon_pocket = IF Baroon_pocket_dam >(Baroon_pocket_capacity - Stream_flow_to_Baroon_pocket) THEN (Baroon_pocket_dam - Baroon_pocket_capacity +Stream_flow_to_Baroon_pocket) ELSE 0
- Caboolture_wier(t) = Caboolture_wier(t - dt) + (Streamflow_to_caboolture_wier - Caboolture_wire_to_TP) * dt
- INIT Caboolture_wier = 450

INFLOWS:

- Streamflow_to_caboolture_wier = Catchment_area_Caboolture*Coefficint_Coefficient_Caboolture*Rainfall_Caboolture

OUTFLOWS:

- Caboolture_wire_to_TP = Caboolture_TP_capacity
- Ewen_Maddock_Dam(t) = Ewen_Maddock_Dam(t - dt) + (Streem_flow_to_Ewen_Maddock - Ewen_Maddock_to_TP - EM_lossess - Relaease__Ewen_Maddock) * dt
- INIT Ewen_Maddock_Dam = 16587

INFLOWS:

- Streem_flow_to_Ewen_Maddock = Catchmetn_Area_EM*Coefficient_EM*Rainfall_EM

- OUTFLOWS:
- Ewen_Maddock_to_TP = IF Ewen_Maddock_Dam< EM_capacity*0.2 Then 0 Else EM_TP_capactiy
- EM_lossess = evaporation_1*0.75*S_area_EM
- Relaease__Ewen_Maddock = IF Ewen_Maddock_Dam > (EM_capacity - Streem_flow_to_Ewen_Maddock) THEN (Ewen_Maddock_Dam -EM_capacity +Streem_flow_to_Ewen_Maddock) ELSE 0
- Gold_coast_SS(t) = Gold_coast_SS(t - dt) + (Stream_flow_to_GC_ss - Gold_coast_ss_to_TP - GC_ss_losses - Release_GC_ss) * dt
- INIT Gold_coast_SS = 317435

INFLOWS:

- Stream_flow_to_GC_ss = Catchmetn_A_Gold_coast_ss*Coefficient_GCSS*Rainfall_Gold_coast_ss

OUTFLOWS:

- Gold_coast_ss_to_TP = IF Gold_coast_SS < Gold_coast_ss_capacity*0.2 THEN 0 ELSE Gold_coast_SS_TP_capacity
- GC_ss_losses = Evaporation_3 *0.75 *GC_ss_S_area
- Release_GC_ss = IF Gold_coast_SS >(Gold_coast_ss_capacity - Stream_flow_to_GC_ss) THEN (Gold_coast_SS -Gold_coast_ss_capacity +Stream_flow_to_GC_ss) Else 0
- Lake_Kurwongbah(t) = Lake_Kurwongbah(t - dt) + (Stream_flow_to_Lake_Kurwongbah - Lake_Kurwongbah_to_TP - Kurwongbah_Lossess - Release_LAke_Kurwongbah) * dt
- INIT Lake_Kurwongbah = 14370

INFLOWS:

- Stream_flow_to_Lake_Kurwongbah = Catchmetn_Area_Kurwongbah*coefficient_Kurwongbah*Rainfall_Kurwongbah

OUTFLOWS:

- Lake_Kurwongbah_to_TP = IF Lake_Kurwongbah <Lake_Kurwongbah_capacity*.2 Then 0 Else Lake_Kurwangbah_TP_capacity
- Kurwongbah_Lossess = Evaporaion_5 *0.75*Kake_Kurwongbah_S_area
- Release_LAke_Kurwongbah = IF Lake_Kurwongbah >(Lake_Kurwongbah_capacity - Stream_flow_to_Lake_Kurwongbah) THEN (Lake_Kurwongbah - Lake_Kurwongbah_capacity +Stream_flow_to_Lake_Kurwongbah) ELSE 0
- Lake_Mac_donald(t) = Lake_Mac_donald(t - dt) + (Stream_flow_to_lake_macdonald - Lake_mac_donald_to_TP - Lake_Mac_D_lossess - Release_Lake_mac_donald) * dt
- INIT Lake_Mac_donald = 8018

INFLOWS:

- Stream_flow_to_lake_macdonald = Catchment_A_Lake_Mac_D*Coefficient_Lake_Mac_D*Rainfall_Lake_Macdonald

OUTFLOWS:

- Lake_mac_donald_to_TP = IF Lake_Mac_donald < Mac_donald_capacity* 0.2 Then 0 Else Lake_mac_donalds_TP_capacity
- Lake_Mac_D_lossess = evaporation_1*0.75*S_area_Macdonald
- Release_Lake_mac_donald = IF Lake_Mac_donald > (Mac_donald_capacity - Stream_flow_to_lake_macdonald) THEN (Lake_Mac_donald -Mac_donald_capacity +Stream_flow_to_lake_macdonald) ELSE 0
- Lesile_H_dam(t) = Lesile_H_dam(t - dt) + (Streamflow_to_LH - LH_to_TP - LH_lossess - Release_LH) * dt
- INIT Lesile_H_dam = 24868

INFLOWS:

- Streamflow_to_LH = Catchment_A_LH*coefficietn_LH*Rainfall_LH

OUTFLOWS:

- LH_to_TP = IF Lesile_H_dam <0.2*LH_capacity THEN 0 ELSE Redland_TP_capaicty
- LH_lossess = Evaporation_4 *0.75 *LH__S__area
- Release_LH = IF Lesile_H_dam >(LH_capacity -Streamflow_to_LH)THEN (Lesile_H_dam -LH_capacity +Streamflow_to_LH) ELSE 0
- Maroochy_ss(t) = Maroochy_ss(t - dt) + (Streem_flow_to_Maroochy_ss - Maroochy_to_TP - Maroochy_lossess - Release_Maroochy_ss) * dt
- INIT Maroochy_ss = 18494

INFLOWS:

- Streem_flow_to_Maroochy_ss = Catchmet_A__Maroochy_ss*Coefficietn_maroocny_ss*Rainfall_Maroochy_SS

OUTFLOWS:

- Maroochy_to_TP = IF Maroochy_ss<Maroochy_ss_capacity*0.2 Then 0 Else Maroochy_SS__TP_capacity
- Maroochy_lossess = evaporation_1*0.75*S_area_Cooloolabin
- Release_Maroochy_ss = IF Maroochy_ss >(Maroochy_ss_capacity-Streem_flow_to_Maroochy_ss) THEN (Maroochy_ss -Maroochy_ss_capacity +Streem_flow_to_Maroochy_ss) ELSE 0
- Maroon_Dam(t) = Maroon_Dam(t - dt) + (Stream_flow_to_Maroon - Maroon_to_TP - Maroon_lossess - Release_Maroon) * dt
- INIT Maroon_Dam = 45310

INFLOWS:

- Stream_flow_to_Maroon = Catchment_A_Maroon*Coefficient_Maroon*Rainfall_Maroon

OUTFLOWS:

- Maroon_to_TP = IF Maroon_Dam <0.2*Maroon_capacity Then 0 Else Maroon_TP_capacity
- Maroon_lossess = Evaporation_2 *0.75*S_area_Maroon
- Release_Maroon = IF Maroon_Dam >(Maroon_capacity-Stream_flow_to_Maroon) THEN (Maroon_Dam -Maroon_capacity +Stream_flow_to_Maroon) Else 0
- Moogerah_Dam(t) = Moogerah_Dam(t - dt) + (Stream_flow_to_Moogerah - Moogerah_to_TP - Moogerah_lossess - Release_Moogerah) * dt
- INIT Moogerah_Dam = 83765

INFLOWS:

- Stream_flow_to_Moogerah = Catchmetn_area_Moogerah*Coefficient_Mooerah*Rainfall_Moogerah

OUTFLOWS:

- Moogerah_to_TP = If Moogerah_Dam< 0.2*Moogerah_capacity Then 0 Else Moogerah_TP_capacity
- Moogerah_lossess = Evaporation_2*0.75*S_area_Moogarah
- Release_Moogerah = IF Moogerah_Dam > (Moogerah_capacity - Stream_flow_to_Moogerah) THEN (Moogerah_Dam -Moogerah_capacity +Stream_flow_to_Moogerah) ELSE 0
- North_pine_dam(t) = North_pine_dam(t - dt) + (Stream_flow_to_North_pine - North_pine_lossess - North_pine_to_TP - Release_North_pine) * dt
- INIT North_pine_dam = 214302

INFLOWS:

- Stream_flow_to_North_pine = Catchmetn_A_NP*Coefficient_NP*Rainfall_NP

OUTFLOWS:

- North_pine_lossess = Evaporaion_5 *0.75 *North_pine_S_area
- North_pine_to_TP = IF North_pine_dam < 0.2*North_pine_capacity THEN 0 Else North_Pine_TP_capacity
- Release_North_pine = IF North_pine_dam >(North_pine_capacity - Stream_flow_to_North_pine) THEN (North_pine_dam -North_pine_capacity +Stream_flow_to_North_pine) ELSE 0
- Somerset_dam(t) = Somerset_dam(t - dt) + (streamflwo_to_Somerset - Somerset_to_TP - Somerset_lossess - Release_Somerset) * dt

- INIT Somerset_dam = 379849

INFLOWS:

- streamflwo_to_Somerset = Catchement_Area_Soversit*Coefficient_Somerset*Rainfall_Somerset

OUTFLOWS:

- Somerset_to_TP = IF Somerset_dam < somerset_capacity*0.2 Then 0 Else Somerset_TP_capacity
- Somerset_lossess = Evaporaion_5 *0.75*Somerset_S_area
- Release_Somerset = If Somerset_dam >(somerset_capacity - streamflwo_to_Somerset) Then (Somerset_dam-somerset_capacity +streamflwo_to_Somerset) Else 0
- Wivenhoe_dam(t) = Wivenhoe_dam(t - dt) + (Stream_flwo_to_Wivenhoe - Wivenhoe_lossess - Toowoomba_pipe_line - Release_Wivenhow - Wivenhoe_to_TP) * dt
- INIT Wivenhoe_dam = 1165240

INFLOWS:

- Stream_flwo_to_Wivenhoe = Catchment_A_Wivnhoe*Coeffient_wivenhoe*Rainfall_Wivenhoe

OUTFLOWS:

- Wivenhoe_lossess = Evaporaion_5 *0.75*Wivenhoe_S_area
- Toowoomba_pipe_line = 0
- Release_Wivenhow = IF Wivenhoe_dam >(Wivenhoe_capacity - Stream_flwo_to_Wivenhoe) THEN (Wivenhoe_dam-Wivenhoe_capacity +Stream_flwo_to_Wivenhoe) Else 0
- Wivenhoe_to_TP = IF Wivenhoe_dam < Wivenhoe_capacity * 0.2 Then 0 Else Wivenhoe_TP_capacity
- Ave_Evaporation_1 = 125
- Av_evaporation_2 = 125
- Av_evaporation_3 = 125
- Av_evaporation_4 = 125
- Av_evaporation_5 = 125
- Baroon_pocket_capacity = 61000
- Baroon_pocket_TP_capacity = If Rainfall_Baroon_Pocket >MEAN(Rainfall_Baroon_Pocket) Then 0.8*4021 else 4021
- Caboolture_TP_capacity = If Rainfall_Caboolture >MEAN(Rainfall_Caboolture) then 0.8*420 else 420
- Catchement_Area_Soversit = 1340
- Catchment_area_Caboolture = 468

- Catchment_A_Lake_Mac_D = 49
- Catchment_A_LH = 87
- Catchment_A_Maroon = 106
- Catchment_A_Wivnhoe = 7020
- Catchmetn_Area_Baroon_pocket = 72
- Catchmetn_Area_EM = 21
- Catchmetn_Area_Kurwongbah = 53
- Catchmetn_area_Moogerah = 228
- Catchmetn_A_Gold_coast_ss = 242.2
- Catchmetn_A_NP = 348
- Catchmet_A__Maroochy_ss = 77.8
- Coefficient_Baroon_pocket = If Rainfall_Baroon_Pocket < 50 then 0 else 0.72
- Coefficient_EM = If Rainfall_EM < 50 Then 0 else 0.8
- Coefficient_GCSS = If Rainfall_Gold_coast_ss < 50 then 0 else 0.95
- coefficient_Kurwongbah = If Rainfall_Kurwongbah < 50 then 0 else 0.8
- Coefficient_Lake_Mac_D = If Rainfall_Lake_Macdonald < 50 then 0 else 0.8
- Coefficient_Maroon = If Rainfall_Maroon < 50 then 0 else 0.2
- Coefficient_Mooerah = IF Rainfall_Moogerah < 50 Then 0 else 0.1
- Coefficient_NP = If Rainfall_NP < 50 Then 0 else 0.5
- Coefficient_Somerset = IF Rainfall_Somerset <50 Then 0*0.15 else 0.15
- coefficietn_LH = If Rainfall_LH < 50 then 0 else 0.15
- Coefficietn_maroocny_ss = IF Rainfall_Maroochy_SS < 50 Then 0 else 0.704
- Coefficint_Coefficient_Caboolture = IF Rainfall_Caboolture < 0.75 then 0 Else 0.58
- Coeffient_wivenhoe = If Rainfall_Wivenhoe <50 then 0*0.15 else 0.15
- Drought_period_factor = 1
- EM_capacity = 16587
- EM_TP_capactiy = IF Rainfall_EM >MEAN(Rainfall_EM) THEN 0.8*608 Else 608
- Evaporaion_5 = Av_evaporation_5*Evaporation_change
- evaporation_1 = Ave_Evaporation_1*Evaporation_change
- Evaporation_2 = Av_evaporation_2*Evaporation_change
- Evaporation_3 = Av_evaporation_3*Evaporation_change
- Evaporation_4 = Av_evaporation_4*Evaporation_change
- Evaporation_change = 1.03
- Exp_RF_Baroon_pocket = EXP(Log_RF_Baroon_pocket)
- Exp_RF_caboolture = EXP(Log_RF_caboolture)
- Exp_RF_EM = EXP(Log_RF_EM)
- Exp_RF_GC = EXP(Log_RF_Gold_Coast)
- Exp_RF_Kurwongbah = EXP(Log_RF_Kurwangbah)
- Exp_RF_LH = EXP(Log_RF_LH)
- Exp_RF_Macdonald = EXP(Log_RF_Macdonald)
- Exp_RF_maroochy = EXP(Log__RF_Maroochy_ss)
- Exp_RF_Maroon = EXP(Log_RF_Maroon)

- Exp_RF_Moogerah = EXP(Log_RF_Moogerah)
- Exp_RF_NP = EXP(Log_RF_NP)
- Exp_RF_Somerset = EXP(log_RF_Somerset)
- Exp_RF_Wivernhoe = EXP(Log_RF_Wivenhoe)
- GC_ss_S_area = GRAPH(Gold_coast_SS)
- (0.00, 0.00), (31744, 0.975), (63487, 1.43), (95231, 2.55), (126974, 3.22), (158718, 5.65), (190461, 6.66), (222205, 8.67), (253948, 11.9), (285692, 13.9), (317435, 15.2)
- Gold_coast_ss_capacity = 317435
- Gold_coast_SS_TP_capacity = If Rainfall_Gold_coast_ss >MEAN(Rainfall_Gold_coast_ss) Then 0.8*8060 else 8060
- Kake_Kurwongbah_S_area = GRAPH(Lake_Kurwongbah)
- (0.00, 0.00), (1437, 0.082), (2874, 0.148), (4311, 0.344), (5748, 0.82), (7185, 1.15), (8622, 1.51), (10059, 1.98), (11496, 2.38), (12933, 2.90), (14370, 3.23)
- Lake_Kurwangbah_TP_capacity = If Rainfall_Kurwongbah >MEAN(Rainfall_Kurwongbah) Then 0.8*1369 Else 1369
- Lake_Kurwongbah_capacity = 14370
- Lake_mac_donalds_TP_capacity = IF Rainfall_Lake_Macdonald>MEAN(Rainfall_Lake_Macdonald) Then 0.8*912.5 Else 912.5
- LH_capacity = 24868
- LH__S__area = GRAPH(Lesile_H_dam)
- (0.00, 0.00), (2487, 0.00), (4974, 0.647), (7460, 0.934), (9947, 1.32), (12434, 1.56), (14921, 2.11), (17408, 2.80), (19894, 3.74), (22381, 4.19), (24868, 4.74)

- Log_RF_Baroon_pocket = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.97,0.83) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.33,0.81) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(5.18,0.53) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.67,0.95) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.62,0.88) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(4.24,0.87) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.46,1.09) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.85,1.22) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.78,1.49) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.46,0.94) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.66,0.60) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.21,0.48) else 9999999

- Log_RF_caboolture = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.61,1.17) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.16,0.84) else if Time= 3 or Time =15 or Time =27 or time

=39 or time = 51 then NORMAL(4.94,0.66) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.23,1.05) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.42,0.98) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.91,1.03) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.01,1.29) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.06,1.93) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.39,1.36) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.34,0.84) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.61,0.68) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.05,0.64) else 9999999

- Log_RF_EM = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.65,0.87) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.21,0.68) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.97,0.58) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.78,0.94) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.87,0.88) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(4.43,0.79) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.67,1.32) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.78,1.46) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.68,0.96) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.23,0.74) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.69,0.89) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.07,0.72) else 999999
- Log_RF_Gold_Coast = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.71,1.12) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.00,1.04) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.65,0.82) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.03,1.06) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.25,0.88) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.87,1.16) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.25,1.40) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.06,1.58) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.61,0.84) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.43,0.73) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.70,0.65) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.92,0.54) else 9999999

- Log_RF_Kurwangbah = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.65,0.92) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.93,0.72) else if Time= 3 or Time =15 or Time =27 or time

=39 or time = 51 then NORMAL(4.67,0.60) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.07,0.94) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.19,0.81) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.61,1.14) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.76,1.55) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.29,1.65) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.55,0.99) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.37,0.83) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.49,0.69) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.92,0.51) else 9999999

- Log_RF_LH = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.44,1.04) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.81,0.66) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.40,0.79) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.21,0.69) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.28,0.79) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.80,0.95) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.97,1.49) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.58,1.14) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.34,1.10) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.23,0.61) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.45,0.69) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.9,0.49) else 9999999

- Log_RF_Macdonald = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(5.06,0.98) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.24,0.86) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(5.04,0.76) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.78,0.97) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(4.86,0.67) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(4.23,0.89) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.74,1.10) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.64,1.44) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.53,1.58) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.06,1.27) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.6,0.65) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.08,0.49) else 9999999

- Log_RF_Maroon = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.4,0.89) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.47,0.75) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.25,0.68) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(3.34,1.26) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(3.14,1.17) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.04,1.45) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.52,1.83) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(2.76,1.63) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.28,0.96) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.15,1.03) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.54,0.57) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.73,0.66) else 999999

- Log_RF_Moogerah = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.42,1.04) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.6,0.69) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.24,0.74) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(3.52,0.78) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(3.52,0.88) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.25,0.92) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.21,1.17) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(2.92,1.25) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.00,1.19) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.41,0.67) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.70,0.57) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.76,0.66) else 9999999

- Log_RF_NP = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.72,0.81) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.84,0.8) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(4.35,0.81) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(4.08,0.98) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(3.90,0.88) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.57,1.16) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.58,1.22) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.08,1.57) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.2,1.49) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.24,0.82) else if Time= 11 or Time =23 or Time =35 or time =47 or time =

59 then NORMAL(4.51,0.56) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.0,0.43) else 9999999

- log_RF_Somerset = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.24,1.16) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.51,0.92) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(3.97,1.0) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(3.55,1.10) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(3.86,0.97) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.43,0.99) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.86,1.48) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.19,1.2) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.24,1.21) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.12,0.79) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.08,0.92) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.92,0.36) else 9999999

- Log_RF_Wivenhoe = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.24,0.93) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(4.19,1.01) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(3.63,1.08) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(3.35,0.94) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(3.32,0.84) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(3.23,1.09) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(2.29,1.73) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(2.80,1.3) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.16,1.88) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(3.9,1.06) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(3.99,0.92) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(4.59,0.39) else 9999999

- Log__RF_Maroochy_ss = If Time= 1 or Time =13 or Time =25 or time =37 or time = 49 then NORMAL(4.86,0.93) else if Time= 2 or Time =14 or Time =26 or time =38 or time = 50 then NORMAL(5.08,0.68) else if Time= 3 or Time =15 or Time =27 or time =39 or time = 51 then NORMAL(5.01,0.71) else if Time= 4 or Time =16 or Time =28 or time =40 or time = 52 then NORMAL(5.04,0.76) else if Time= 5 or Time =17 or Time =29 or time =41 or time = 53 then NORMAL(5.01,0.47) else if Time= 6 or Time =18 or Time =30 or time =42 or time = 54 then NORMAL(4.27,0.84) else if Time= 7 or Time =19 or Time =31 or time =43 or time = 55 then NORMAL(3.61,1.52) else if Time= 8 or Time =20 or Time =32 or time =44 or time = 56 then NORMAL(3.55,1.64) else if Time= 9 or Time =21 or Time =33 or time =45 or time = 57 then NORMAL(3.68,1.20) else if Time= 10 or Time =22 or Time =34 or time =46 or time = 58 then NORMAL(4.31,0.73) else if Time= 11 or Time =23 or Time =35 or time =47 or time = 59 then NORMAL(4.47,1.16) else if Time= 12 or Time =24 or Time =36 or time =48 or time = 60 then NORMAL(5.05,0.70) else 9999999

- Mac_donald_capacity = 8018
- Maroochy_ss_capacity = 18494
- Maroochy_SS__TP_capacity = If Rainfall_Maroochy_SS>MEAN(Rainfall_Maroochy_SS) THEN 0.8 *548 Else 548
- Maroon_capacity = 45310
- Maroon_TP_capacity = IF Rainfall_Maroon >MEAN(Rainfall_Maroon) Then 0.8*569 else 569
- Monthly_GW_extractions = 750
- Moogerah_capacity = 83765
- Moogerah_TP_capacity = If Rainfall_Moogerah >MEAN(Rainfall_Moogerah) Then 0.8*107 Else 107
- North_pine_capacity = 214302
- North_pine_S_area = GRAPH(North_pine_dam)
- (0.00, 0.00), (21430, 12.5), (42860, 24.5), (64291, 30.0), (85721, 37.5), (107151, 42.0), (128581, 45.0), (150011, 50.0), (171442, 58.0), (192872, 72.5), (214302, 99.5)
- North_Pine_TP_capacity = If Rainfall_NP> MEAN(Rainfall_NP) Then 0.8*6600 Else 6600
- NSI_Ground_water_treatmetn_capacity = 780
- Rainfall_Baroon_Pocket = Exp_RF_Baroon_pocket*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Caboolture = Exp_RF_caboolture*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_EM = Exp_RF_EM*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Gold_coast_ss = Exp_RF_GC*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_incriemt_factor = 0.8
- Rainfall_Kurwongbah = Exp_RF_Kurwongbah*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Lake_Macdonald = Exp_RF_Macdonald*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_LH = Exp_RF_LH*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Maroochy_SS = Exp_RF_maroochy*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Maroon = Exp_RF_Maroon*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Moogerah = Exp_RF_Moogerah*Rainfall_incriemt_factor*Drought_period_factor

- Rainfall_NP = Exp_RF_NP*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Somerset = Exp_RF_Somerset*Rainfall_incriemt_factor*Drought_period_factor
- Rainfall_Wivenhoe = Exp_RF_Wivernhoe*Rainfall_incriemt_factor*Drought_period_factor
- Redland_TP_capaicty = If Rainfall_LH >MEAN(Rainfall_LH) Then 0.8*548 Else 548
- somerset_capacity = 379849
- Somerset_S_area = GRAPH(Somerset_dam)
- (0.00, 0.00), (37985, 10.7), (75970, 30.5), (113955, 36.2), (151940, 38.3), (189925, 40.0), (227909, 40.2), (265894, 41.3), (303879, 41.5), (341864, 41.7), (379849, 41.5)
- Somerset_TP_capacity = If Rainfall_Somerset >MEAN(Rainfall_Somerset) Then 0.8*648 Else 648
- S_area_Baroon_pocket = GRAPH(Baroon_pocket_dam)
- (0.00, 0.1), (5545, 0.34), (11091, 0.56), (16636, 0.72), (22182, 0.9), (27727, 1.22), (33273, 1.50), (38818, 1.78), (44364, 2.34), (49909, 2.56), (55455, 3.66), (61000, 4.00)
- S_area_Cooloolabin = GRAPH(Maroochy_ss)
- (0.00, 0.00), (1898, 0.275), (3797, 0.627), (5695, 0.869), (7594, 1.20), (9492, 1.38), (11390, 1.60), (13289, 1.95), (15187, 2.15), (17086, 2.55), (18984, 2.92)
- S_area_EM = GRAPH(Ewen_Maddock_Dam)
- (0.00, 0.00), (1659, 0.278), (3317, 0.481), (4976, 0.611), (6635, 0.907), (8294, 1.18), (9952, 1.30), (11611, 1.78), (13270, 2.20), (14928, 2.87), (16587, 3.59)
- S_area_Macdonald = GRAPH(Lake_Mac_donald)
- (0.00, 0.00), (802, 0.143), (1604, 0.169), (2405, 0.403), (3207, 0.663), (4009, 0.975), (4811, 1.26), (5613, 1.55), (6414, 1.83), (7216, 2.44), (8018, 2.57)
- S_area_Maroon = GRAPH(Maroon_Dam)
- (0.00, 0.00), (4531, 0.109), (9062, 0.403), (13593, 0.635), (18124, 0.806), (22655, 1.13), (27186, 1.57), (31717, 1.88), (36248, 2.36), (40779, 2.70), (45310, 3.08)
- S_area_Moogarah = GRAPH(Moogerah_Dam)
- (0.00, 0.00), (8377, 1.24), (16753, 3.31), (25130, 4.18), (33506, 5.09), (41883, 5.71), (50259, 6.04), (58636, 6.53), (67012, 7.03), (75389, 7.57), (83765, 8.23)
- Wivenhoe_capacity = 1165238
- Wivenhoe_S_area = GRAPH(Wivenhoe_dam)
- (0.00, 0.00), (116500, 96.5), (233000, 101), (349500, 101), (466000, 102), (582500, 104), (699000, 104), (815500, 105), (932000, 106), (1e+006, 105), (1.2e+006, 108)
- Wivenhoe_TP_capacity = If Rainfall_Wivenhoe >MEAN(Rainfall_Wivenhoe) Then 0.8*28470 Else 28470

Appendix B

Runoff coefficient derivation and verification

Table B.1: Wivenhoe Catchment-Streamflow and Rainfall data

Streamflow gauge no (DERM) 143009A - Brisbane River at Gregors Creek

Rainfall gauge station no (BOM) – 40205

Month	Streamflow (ML/day)	Streamflow (ML/month)	Streaflow(mm/month)	Rainfall (mm/month)
Jun-09	117.862	3535.86	0.91	70.6
Jul-09	80.592	2417.76	0.63	0
Aug-09	16.432	492.96	0.13	2.8
Sep-09	6.771	203.13	0.05	14.6
Oct-09	0.219	6.57	0.00	54
Nov-09	0.317	9.51	0.00	35.4
Jan-10	1.028	30.84	0.01	76.6
Feb-10	276.667	8300.01	2.15	130
Mar-10	5447.792	163433.76	42.27	184.4
Apr-10	328.59	9857.7	2.55	72
May-10	47.636	1429.08	0.37	31.2
Jun-10	29.425	882.75	0.23	8.6
Jul-10	23.275	698.25	0.18	28.2
Aug-10	139.582	4187.46	1.08	104.4
Sep-10	1361.641	40849.23	10.57	191.4
Oct-10	6217.881	186536.43	48.25	220.4
Nov-10	309.345	9280.35	2.40	8.8
Dec-10	11378.989	341369.67	88.30	315.6
Jan-11	36242.107	1087263.21	281.24	424.4
Feb-11	1165.041	34951.23	9.04	55
Mar-11	1753.344	52600.32	13.61	208.6
Apr-11	591.842	17755.26	4.59	38.4
May-11	574.675	17240.25	4.46	75.4
Jun-11	478.205	14346.15	3.71	6.8
Jul-11	259.104	7773.12	2.01	16
Aug-11	234.647	7039.41	1.82	48.6
Sep-11	196.855	5905.65	1.53	14.4
Oct-11	161.035	4831.05	1.25	76.8
Nov-11	87.991	2639.73	0.68	6.8
Dec-11	141.507	4245.21	1.10	124.4
Jan-12	1231.797	36953.91	9.56	27.4

Table B.2: Somerset Catchment Streamflow and Rainfall data

Streamflow gauge station no (DERM) 143303A

Rainfall gauge station no (BOM) 40169

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Aug-08	52.537	1576.11	15.15490385	1.2
Sep-08	178.265	5347.95	51.42259615	148.7
Oct-08	30.717	921.51	8.860673077	43
Dec-08	46.163	1384.89	13.31625	105
Jan-09	40.462	1213.86	11.67173077	117.3
Feb-09	279.132	8373.96	80.51884615	154.1
Mar-09	216.812	6504.36	62.54192308	190.9
May-09	529.669	15890.07	152.7891346	301.2
Jun-09	253.768	7613.04	73.20230769	148.2
Jul-09	83.773	2513.19	24.16528846	2.4
Aug-09	33.476	1004.28	9.656538462	7.4
Sep-09	20.436	613.08	5.895	21
Oct-09	15.378	461.34	4.435961538	103.7
Nov-09	3.01	90.3	0.868269231	37.4
Jan-10	96.613	2898.39	27.86913462	156.7
Feb-10	801.774	24053.22	231.2809615	521.2
Apr-10	183.403	5502.09	52.90471154	98
May-10	80.836	2425.08	23.31807692	39.7
Jul-10	30.473	914.19	8.790288462	55.6
Aug-10	58.269	1748.07	16.80836538	82.5
Sep-10	35.877	1076.31	10.34913462	100.4
Nov-10	99.326	2979.78	28.65173077	77.5
Feb-11	272.217	8166.51	78.52413462	155.5
Mar-11	351.168	10535.04	101.2984615	233.1
Apr-11	463.8	13914	133.7884615	193.1
May-11	190.771	5723.13	55.03009615	88.6
Jun-11	84.914	2547.42	24.49442308	32.2
Jul-11	62.925	1887.75	18.15144231	26.5
Aug-11	78.733	2361.99	22.71144231	93.7
Sep-11	48.03	1440.9	13.85480769	21.6
Nov-11	22.813	684.39	6.580673077	47.1
Dec-11	534.125	16023.75	154.0745192	286.1

Table B.3: Hinze Catchment- Streamflow and Rainfall data

Streamflow gauge station no (DERM) 1146015A

Rainfall gauge station no (DERM) 1146015A

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Jan-09	104.588	3137.64	46.14176471	161
Feb-09	244.674	7340.22	107.9444118	151
Mar-09	94.557	2836.71	41.71632353	84
Apr-09	389.474	11684.22	171.8267647	211
May-09	532.399	15971.97	234.8819118	259
Jun-09	261.334	7840.02	115.2944118	148
Jul-09	61.061	1831.83	26.93867647	6
Aug-09	17.074	512.22	7.532647059	0
Sep-09	5.575	167.25	2.459558824	11
Oct-09	4.157	124.71	1.833970588	55
Nov-09	11.263	337.89	4.968970588	101
Dec-09	59.732	1791.96	26.35235294	209
Jan-10	41.534	1246.02	18.32382353	126
Feb-10	539.761	16192.83	238.1298529	300
Mar-10	246.029	7380.87	108.5422059	125
Apr-10	56.561	1696.83	24.95338235	30
May-10	90.764	2722.92	40.04294118	124
Jun-10	22.286	668.58	9.832058824	8
Jul-10	16.159	484.77	7.128970588	55
Aug-10	20.44	613.2	9.017647059	71
Sep-10	17.623	528.69	7.774852941	81
Oct-10	480.198	14405.94	211.8520588	200
Nov-10	92.02	2760.6	40.59705882	94
Dec-10	864.814	25944.42	381.5355882	431
Jan-11	787.93	23637.9	347.6161765	304
Feb-11	118.073	3542.19	52.09102941	95
Mar-11	104.557	3136.71	46.12808824	124
Apr-11	153.772	4613.16	67.84058824	72
May-11	99.053	2971.59	43.69985294	67
Jun-11	29.952	898.56	13.21411765	19
Jul-11	15.16	454.8	6.688235294	5

Table B.4: North Pine Catchment- Streamflow and Rainfall data

Streamflow gauge station no (DERM) 142106A

Rainfall gauge station no (BOM) 40063

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Apr-01	30.342	910.26	4.816190476	25
May-01	11.548	346.44	1.833015873	11
Jun-01	7.207	216.21	1.143968254	19.5
Aug-01	5.617	168.51	0.891587302	5.4
Sep-01	3.744	112.32	0.594285714	17.6
Jan-03	0.168	5.04	0.026666667	12.6
Mar-03	298.792	8963.76	47.42730159	141.7
Apr-03	159.635	4789.05	25.33888889	66.6
Jun-03	23.521	705.63	3.733492063	38.4
Jul-03	38.23	1146.9	6.068253968	21.8
Aug-03	11.098	332.94	1.761587302	29.8
Sep-03	2.775	83.25	0.44047619	3.7
May-04	21.578	647.34	3.425079365	16.4
Jun-04	11.33	339.9	1.798412698	2.4
Jul-04	4.341	130.23	0.689047619	5.2
Aug-04	1.047	31.41	0.166190476	4
Feb-05	33.075	992.25	5.25	25.2
Mar-05	25.24	757.2	4.006349206	15.6
Jul-05	8.478	254.34	1.345714286	16
Aug-05	4.609	138.27	0.731587302	12.6
Dec-05	151.74	4552.2	24.08571429	98.4
Apr-06	40.768	1223.04	6.471111111	37
May-06	11.77	353.1	1.868253968	8
Oct-06	6.68	200.4	1.06031746	19.2
Apr-07	0.896	26.88	0.142222222	13.2
Jul-07	0.247	7.41	0.039206349	0.8
Sep-07	54.371	1631.13	8.63031746	54
Oct-07	32.346	970.38	5.134285714	50.8
Apr-08	41.708	1251.24	6.62031746	19.8
Jul-08	178.945	5368.35	28.40396825	100.4
Oct-08	74.078	2222.34	11.7584127	50.2
Dec-08	236.548	7096.44	37.54730159	105.2

Table B.5: Ewen Maddock Catchment- Streamflow and Rainfall data

Streamflow gauge station no (DERM) 141006A

Rainfall gauge station no (DERM) 141006A

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Apr-03	105.259	3157.77	80.96846154	164
May-03	89.036	2671.08	68.48923077	167
Jul-03	21.911	657.33	16.85461538	62
Feb-04	114.973	3449.19	88.44076923	188
Jun-05	49.239	1477.17	37.87615385	193
Feb-06	90.451	2713.53	69.57769231	159
Jun-06	3.987	119.61	3.066923077	89.3
Jul-06	10.917	327.51	8.397692308	57.6
Nov-06	0.994	29.82	0.764615385	98
Dec-06	8.432	252.96	6.486153846	74
Jan-07	1.417	42.51	1.09	75.7
Oct-07	106.969	3209.07	82.28384615	60.8
Feb-08	214.978	6449.34	165.3676923	318.4
Jun-08	21.293	638.79	16.37923077	164
Dec-08	100.717	3021.51	77.47461538	81.2
Jan-09	13.455	403.65	10.35	127.2
May-09	447.489	13424.67	344.2223077	246.6
Jun-09	178.894	5366.82	137.6107692	137.1
Oct-09	1.782	53.46	1.370769231	87.8
Nov-09	2.358	70.74	1.813846154	59
Dec-09	0.56	16.8	0.430769231	87
Jan-10	9.068	272.04	6.975384615	115
Mar-10	420.399	12611.97	323.3838462	500.2
May-10	108.233	3246.99	83.25615385	82.8
Aug-10	4.497	134.91	3.459230769	70.6
Jan-11	569.408	17082.24	438.0061538	719.6
Feb-11	782.7	23481	602.0769231	197.4

Table B 6: Lake Macdoneld Catchment- Streamflow and Rainfall data

Streamflow gauge station no (DERM) 138107B

Rainfall gauge station no (DERM) 138107B

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Dec-08	30.298	908.94	4.886774194	85
Jan-09	47.087	1412.61	7.594677419	141
Feb-09	149.985	4499.55	24.19112903	137
Mar-09	231.886	6956.58	37.40096774	118
Apr-09	2668.35	80050.5	430.3790323	558
May-09	404.136	12124.08	65.18322581	160
Jun-09	305.985	9179.55	49.35241935	95
Jul-09	78.613	2358.39	12.67951613	2
Aug-09	18.191	545.73	2.934032258	0
Oct-09	10.743	322.29	1.732741935	19
Nov-09	7.684	230.52	1.239354839	38
Dec-09	5.562	166.86	0.897096774	134
Jan-10	14.957	448.71	2.412419355	113
Mar-10	1685.996	50579.88	271.9348387	367
Apr-10	162.852	4885.56	26.26645161	80
May-10	90.561	2716.83	14.6066129	78
Jun-10	38.638	1159.14	6.231935484	33
Jul-10	18.581	557.43	2.996935484	23
Aug-10	33.432	1002.96	5.392258065	55
Sep-10	58.06	1741.8	9.364516129	111
Oct-10	628.762	18862.86	101.4132258	158
Nov-10	46.354	1390.62	7.476451613	64
Dec-10	1648.249	49447.47	265.8466129	459
Jan-11	3171.336	95140.08	511.5058065	579
Feb-11	341.577	10247.31	55.09306452	146
Mar-11	532.057	15961.71	85.81564516	184
Apr-11	568.741	17062.23	91.73241935	157
May-11	229.743	6892.29	37.05532258	108
Jun-11	85.449	2563.47	13.78209677	23
Jul-11	40.266	1207.98	6.494516129	25
Aug-11	83.829	2514.87	13.52080645	85
Sep-11	52.06	1561.8	8.396774194	28
Oct-11	13.755	412.65	2.218548387	74

Table B 7: Maroon Catchment- Streamflow and Rainfall data

Streamflow gauge station no (DERM) 138107B

Rainfall gauge station no (DERM) 138107B

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Apr-03	12.174	365.22	4.453902439	68.8
Nov-03	0.348	10.44	0.127317073	57.9
Feb-04	44.926	1347.78	16.43634146	154.6
Oct-04	0.059	1.77	0.021585366	75
Nov-05	0.017	0.51	0.006219512	142
Dec-05	0.367	11.01	0.134268293	87.2
Feb-06	21.11	633.3	7.723170732	100.1
Mar-06	2.8	84	1.024390244	53.4
Apr-06	8.095	242.85	2.961585366	63.2
Jul-06	0.221	6.63	0.080853659	69.8
Nov-06	0.195	5.85	0.071341463	66.4
Jan-07	0.029	0.87	0.010609756	79.8
Nov-07	1.303	39.09	0.476707317	133
Dec-07	19.954	598.62	7.300243902	192
Jan-08	37.376	1121.28	13.67414634	186.6
Mar-08	129.005	3870.15	47.19695122	62
Dec-08	48.35	1450.5	17.68902439	155.6
Jan-09	23.912	717.36	8.748292683	137.8
Feb-09	21.741	652.23	7.95402439	62.4
Apr-09	8.05	241.5	2.945121951	78
May-09	40.96	1228.8	14.98536585	121.8
Jun-09	147.67	4430.1	54.02560976	62.8
Nov-09	1.431	42.93	0.523536585	69.4
Jan-10	14.122	423.66	5.166585366	59.1
Mar-10	82.177	2465.31	30.0647561	96.5
May-10	6.104	183.12	2.233170732	59.8
Aug-10	5.244	157.32	1.918536585	53
Sep-10	6.539	196.17	2.392317073	89.9
Nov-10	132.732	3981.96	48.5604878	127.6
Jan-11	431.999	12959.97	158.0484146	249.2
Mar-11	60.208	1806.24	22.02731707	129.1
May-11	69.107	2073.21	25.28304878	85.6
Aug-11	17.861	535.83	6.534512195	79.2

Table B.8: Wappa Catchment (Maroochy subsystm) - Streamflow and Rainfall data

Streamflow gauge station no (DERM) 141001B

Rainfall gauge station no (DERM) 40525

Month	Streamflow (ML/Day)	Streamflow (ML/month)	Streamflow (mm/month)	Rainfall (mm/month)
Aug-96	0.714	21.42	0.649090909	15.2
Sep-96	0.333	9.99	0.302727273	21.2
Oct-96	0.963	28.89	0.875454545	67.2
Nov-96	1.633	48.99	1.484545455	107.6
Dec-96	3.887	116.61	3.533636364	137.6
Jan-97	5.265	157.95	4.786363636	146.8
Feb-97	1.488	44.64	1.352727273	78.4
Mar-97	128.333	3849.99	116.6663636	262.8
Apr-97	7.1	213	6.454545455	87.6
May-97	91.685	2750.55	83.35	189.4
Jun-97	1.162	34.86	1.056363636	29
Jul-97	1.223	36.69	1.111818182	47
Aug-97	0.72	21.6	0.654545455	40
Sep-97	0.038	1.14	0.034545455	31.2
Oct-97	10.249	307.47	9.317272727	142.4
Nov-97	10.889	326.67	9.899090909	96
Dec-97	0.512	15.36	0.465454545	71.6
Jan-98	45.311	1359.33	41.19181818	268.8
Feb-98	15.611	468.33	14.19181818	103.4
Mar-98	0.91	27.3	0.827272727	61.8
Apr-98	48.98	1469.4	44.52727273	201.2
May-98	56.182	1685.46	51.07454545	112.8
Jun-98	3.063	91.89	2.784545455	54.4
Jul-98	3.341	100.23	3.037272727	64.4
Aug-98	4.016	120.48	3.650909091	74.4
Sep-98	133.223	3996.69	121.1118182	209.3
Oct-98	0.927	27.81	0.842727273	11.4
Nov-98	3.853	115.59	3.502727273	126
Jan-99	28.353	850.59	25.77545455	158.4
Feb-99	987.973	29639.19	898.1572727	1132
Mar-99	231.174	6935.22	210.1581818	315.8
Apr-99	59.791	1793.73	54.35545455	151.6

Scatter plots were drawn from above data and the gradient of best fit line was obtained as the runoff coefficient. The scatter plots for rainfall and streamflow for different catchments are given below.

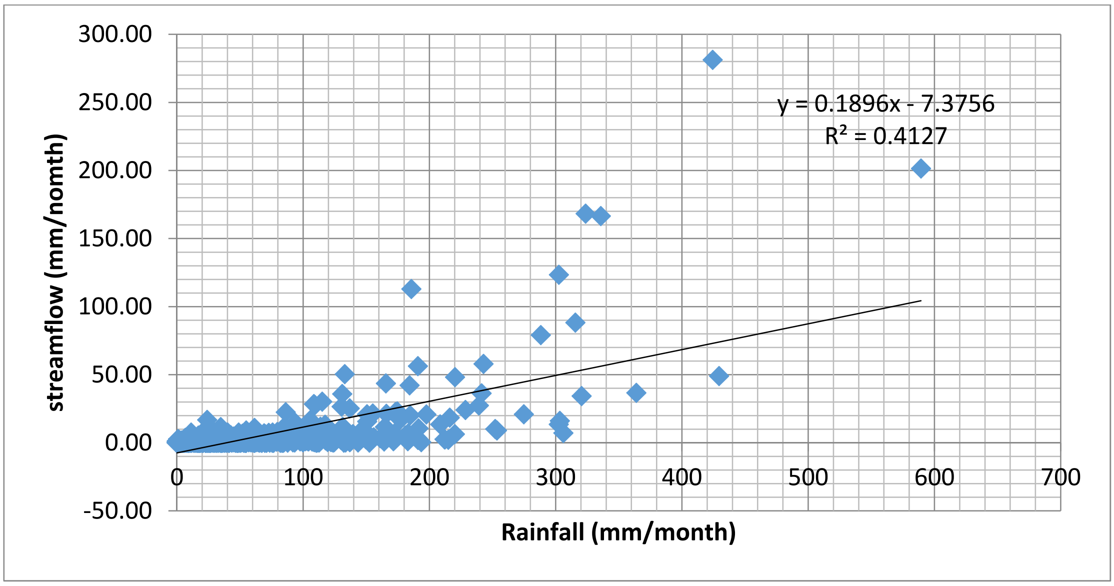

Figure B.1: Scatter plot for Rainfall and Streamflow -Wivenhoe Catchment

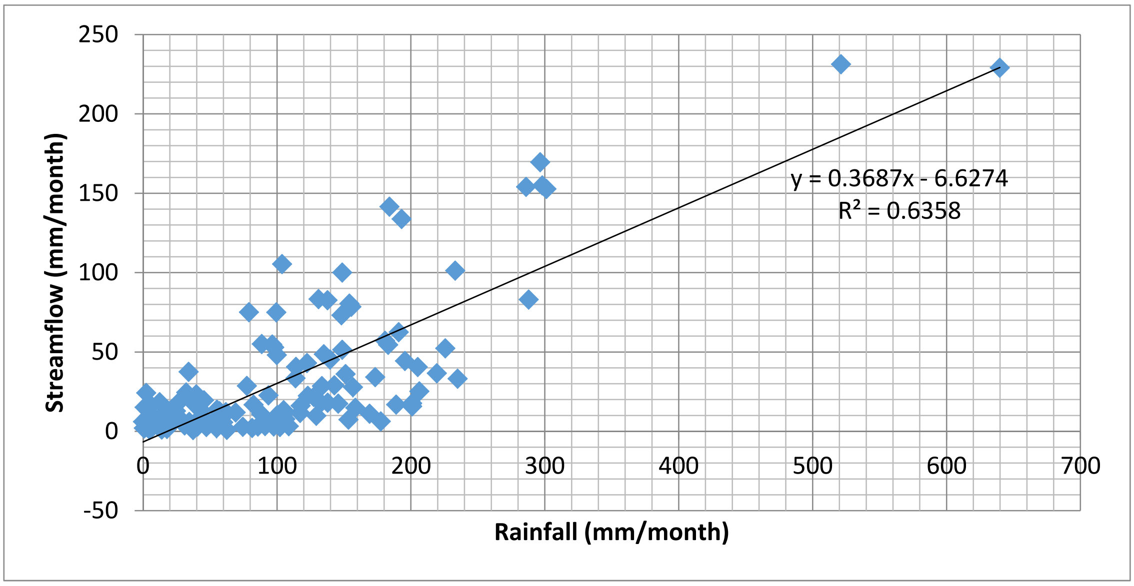

Figure B.2: Scatter plot for Rainfall and Streamflow –Somerset Catchment

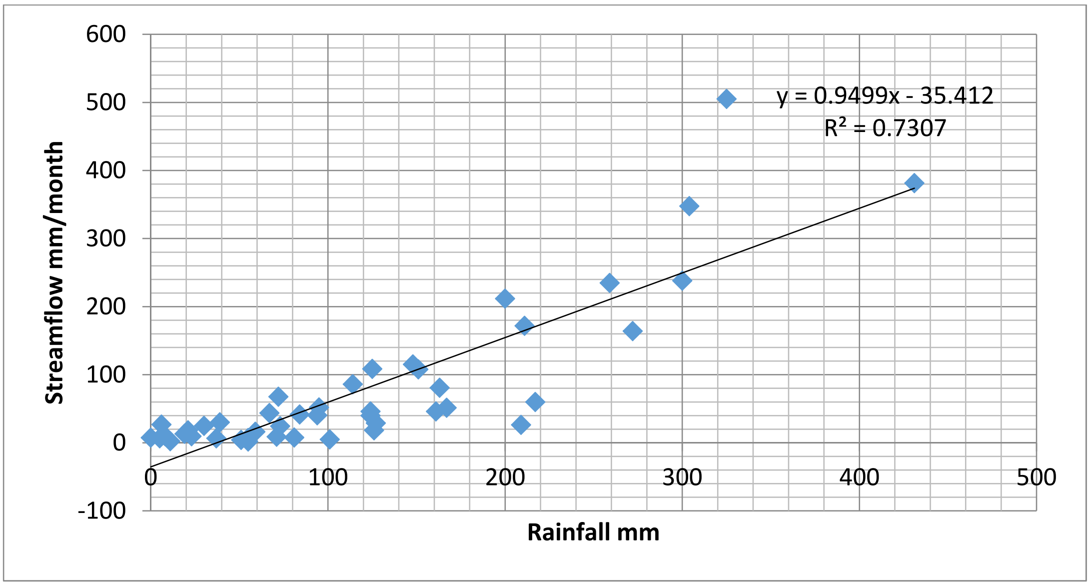

Figure B3: Scatter plot for Rainfall and Streamflow –Hinze Catchment (Gold Coast)

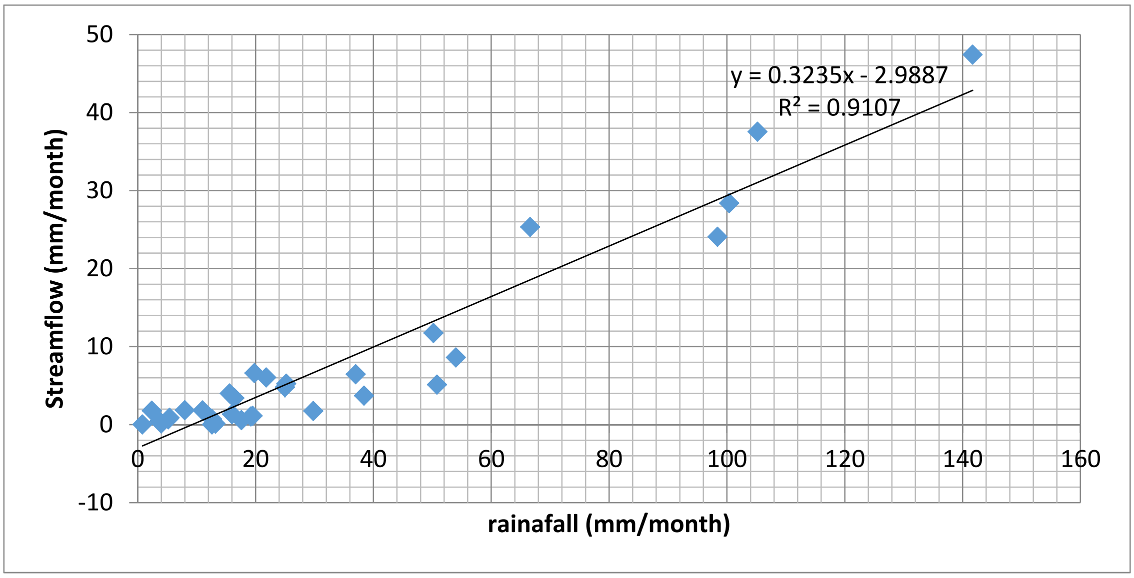

Figure B.4: Scatter plot for Rainfall and Streamflow- North Pine Catchment

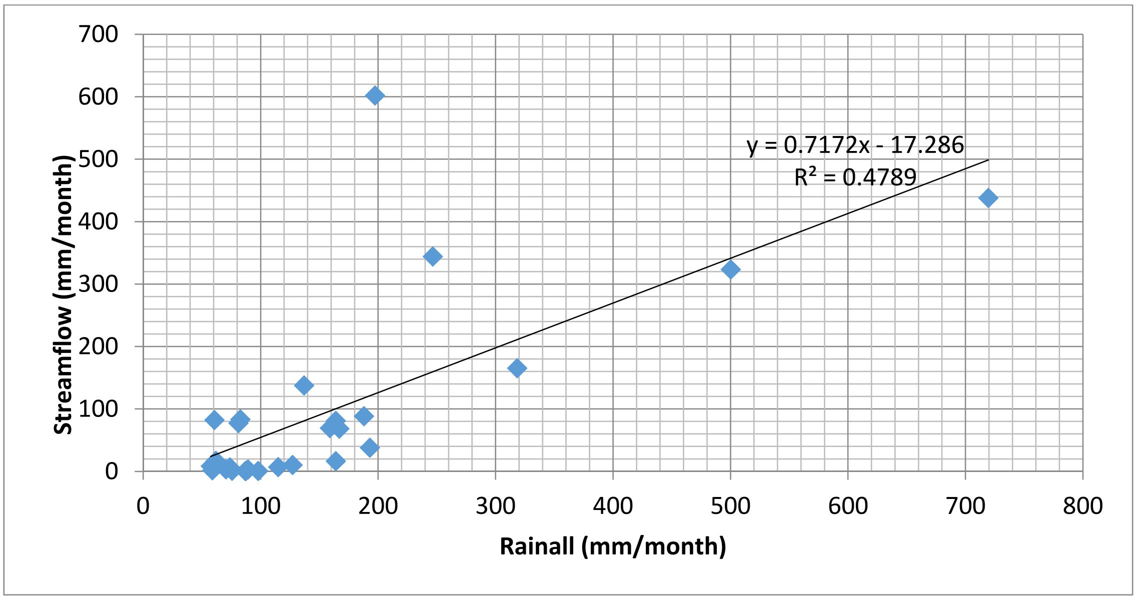

Figure B.5: Scatter plot for Rainfall and Streamflow -Ewen Maddock Catchment

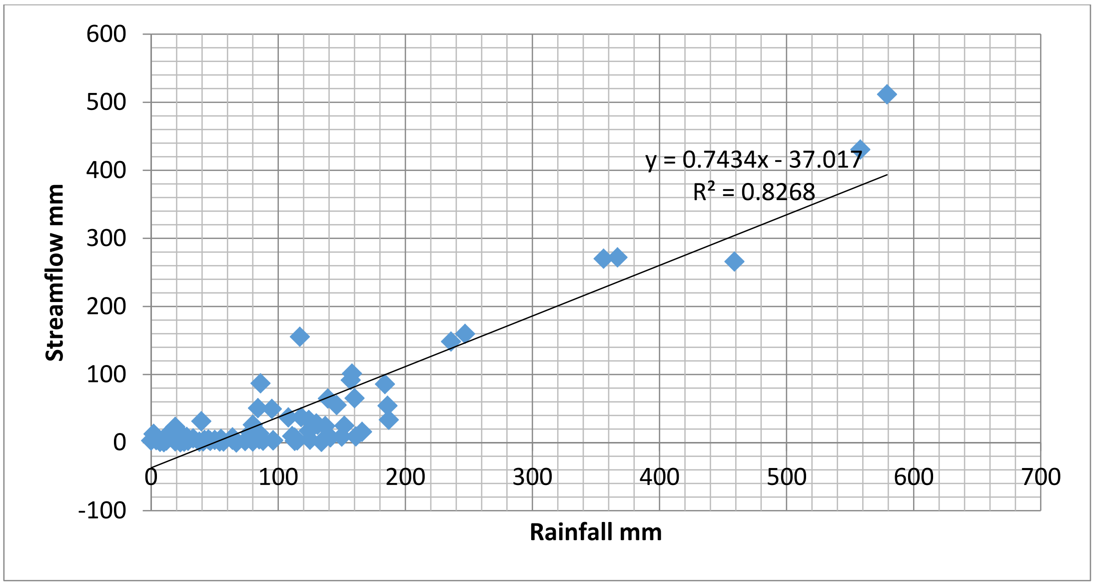

Figure B.6 : Scatter plot for Rainfall and Streamflow -Lake Mc Donald Catchment

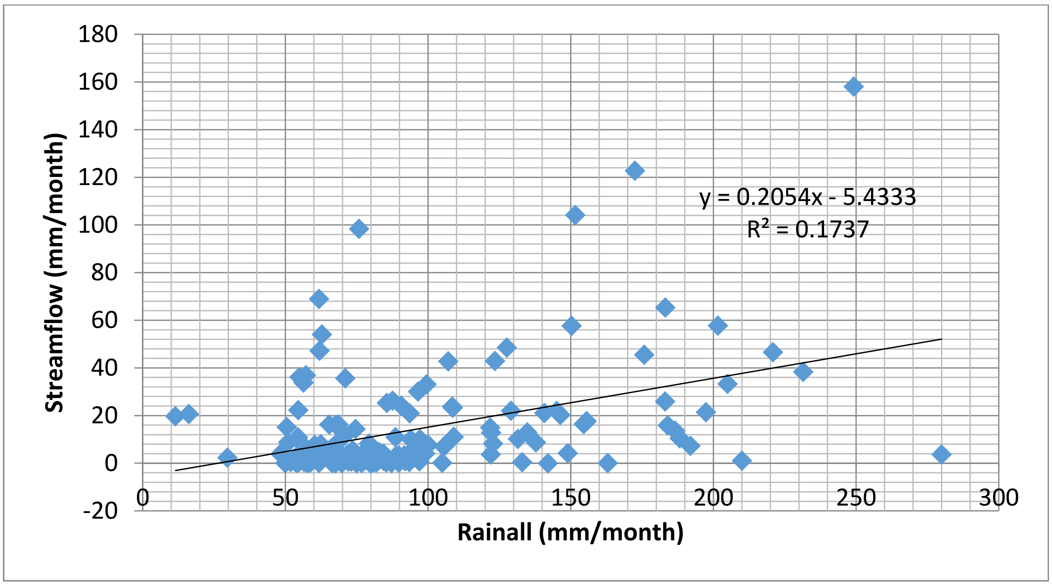

Figure B.7:-Scatter plot for Rainfall and Streamflow- Maroon Catchment

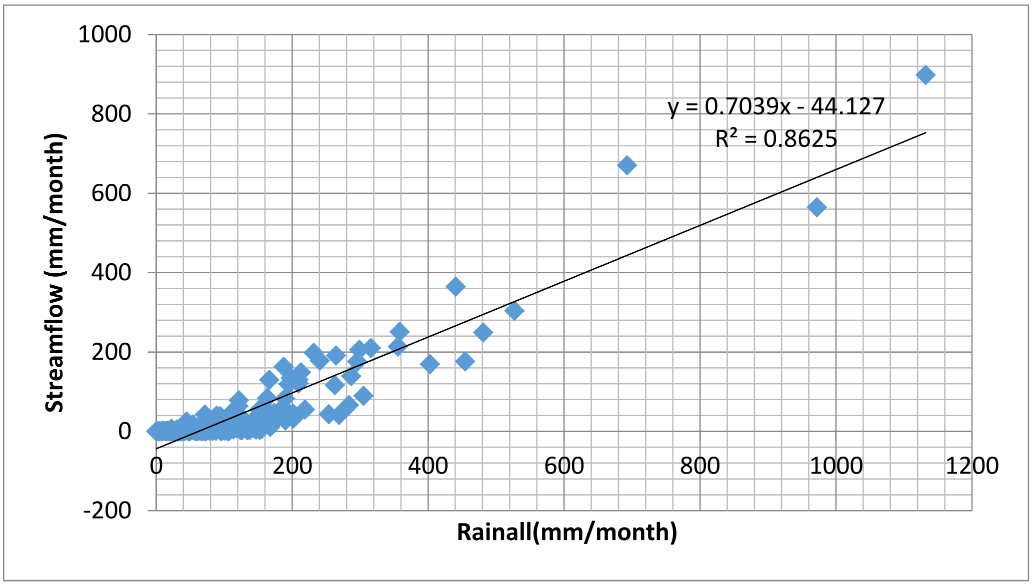

Figure B.8: Scatter plot for Rainfall and Streamflow- Wappa Catchment (Maroochy Subsystem)

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<u>Comparison of actual storage and simulated storage values to verify runoff coefficient values</u>

Actual storage data were obtained from SEQ Water. The actual and simulated data tables and graphs are given below.

Table B.9: Wivenhoe Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jan-08	17.1	199255.698	199,225.00
Feb-08	24.9	290144.262	302,134.74
Mar-08	26.3	306457.594	485,261.50
Apr-08	25.1	292474.738	448,966.12
May-08	24.1	280822.358	412,804.58
Jun-08	25	291309.5	376,801.63
Jul-08	25.4	295970.452	422,458.78
Aug-08	26.8	312283.784	446,645.09
Sep-08	27.3	318109.974	410,493.72
Dec-08	32.6	379867.588	562,615.13
Jan-09	32	372876.16	621,905.27
Feb-09	32.4	377537.112	642,773.82
Mar-09	32.8	382198.064	674,676.03
Apr-09	39.5	460269.01	637,516.16
May-09	46	536009.48	734,104.85
Jun-09	64.7	753908.986	873,622.66
Jul-09	68	792361.84	893,928.66
Aug-09	66.7	777213.746	856,020.00
Oct-09	66.1	770222.318	780,700.74
Nov-09	66.3	772552.794	743,212.36
Dec-09	64.5	751578.51	705,806.19
Jan-10	62.7	730604.226	782,206.04
Feb-10	61.2	713125.656	744,714.37
Mar-10	96.2	1120958.956	811,762.50
Apr-10	96.7	1126785.146	893,826.81
May-10	96.6	1125619.908	855,918.60
Jun-10	94.8	1104645.624	818,176.65
Aug-10	93.7	1091828.006	743,112.07
Sep-10	95.9	1117463.242	778,994.92
Oct-10	102.5	1194368.95	830,594.08
Nov-10	100.3	1168733.714	1,024,623.19

Table B.10: Somerset Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jan-08	54.6	207397.554	207,398.00
Feb-08	82.9	314894.821	244,370.59
Mar-08	80.5	305778.445	282,093.76
Apr-08	82.3	312615.727	291,344.61
May-08	82.1	311856.029	286,815.45
Jun-08	85.6	325150.744	282,288.64
Jul-08	85.3	324011.197	294,487.39
Aug-08	88.2	335026.818	316,435.00
Sep-08	89.4	339585.006	311,892.80
Oct-08	89.8	341104.402	341,710.57
Nov-08	89.6	340344.704	337,155.24
Dec-08	92.9	352879.721	375,296.04
Jan-09	91	345662.59	375,310.96
Feb-09	92.3	350600.627	375,310.97
Mar-09	93.5	355158.815	375,310.97
Apr-09	91	345662.59	375,310.97
May-09	92.7	352120.023	375,310.97
Jun-09	92.9	352879.721	375,310.97
Jul-09	91.9	349081.231	375,310.97
Aug-09	92.9	352879.721	370,772.94
Sep-09	92.7	352120.023	366,232.55
Oct-09	86.6	328949.234	361,689.81
Nov-09	82.5	313375.425	375,303.89
Dec-09	80.2	304638.898	370,765.86
Jan-10	81.7	310336.633	375,308.61
Feb-10	91.8	348701.382	370,770.58
Mar-10	100.1	380228.849	375,308.61
Apr-10	100.5	381748.245	375,310.97
May-10	99.5	377949.755	370,772.94
Jun-10	99.7	378709.453	375,308.61
Jul-10	100	379849	370,770.58
Aug-10	100	379849	366,230.19
Sep-10	100	379849	375,306.25
Oct-10	105.2	399601.148	375,310.97
Nov-10	100.5	381748.245	375,310.97
Dec-10	108.6	412516.014	370,772.94

Table B.11: North Pine Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jan-08	17.2	36,859.94	36,860.00
Feb-08	31.5	67,505.13	67,363.92
Mar-08	32	68,576.64	91,375.01
Apr-08	31.5	67,505.13	91,145.58
May-08	30.4	65,147.81	79,445.70
Jun-08	34.9	74,791.40	75,197.43
Jul-08	34.9	74,791.40	99,817.31
Aug-08	35	75,005.70	87,605.29
Sep-08	35.5	76,077.21	76,114.50
Oct-08	36.1	77,363.02	86,471.79
Nov-08	35.7	76,505.81	83,921.94
Dec-08	43.7	93,649.97	94,733.25
Jan-09	42.7	91,506.95	110,661.49
Feb-09	41.2	88,292.42	112,742.82
Mar-09	45.5	97,507.41	134,147.45
Apr-09	48	102,864.96	128,758.92
May-09	73.3	157,083.37	175,863.38
Jun-09	100	214,302.00	198,647.20
Jul-09	100	214,302.00	198,508.94
Aug-09	100	214,302.00	182,718.30
Sep-09	100	214,302.00	167,048.50
Oct-09	96.7	207,230.03	151,480.25
Nov-09	95.3	204,229.81	150,696.03
Dec-09	92.8	198,872.26	135,413.92
Jan-10	94	201,443.88	156,098.47
Feb-10	99	212,158.98	159,322.43
Mar-10	100	214,302.00	187,145.77
Apr-10	99	212,158.98	198,622.52
May-10	99	212,158.98	194,313.89
Jun-10	98	210,015.96	178,596.66
Jul-10	96	205,729.92	162,935.88
Aug-10	95	203,586.90	147,439.60
Sep-10	96.7	207,230.03	152,112.88
Oct-10	98	210,015.96	153,649.18
Nov-10	99	212,158.98	198,968.22
Dec-10	99	212,158.98	198,503.32

Table B 12: Baroon Pocket Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jul-08	100	61,000.00	61,000.00
Aug-08	100	61,000.00	56,604.00
Sep-08	100	61,000.00	56,629.27
Oct-08	100	61,000.00	52,258.39
Nov-08	97	59,170.00	56,639.12
Dec-08	100	61,000.00	56,444.87
Jan-09	100	61,000.00	56,630.18
Feb-09	97	59,170.00	56,629.12
Mar-09	100	61,000.00	56,629.12
Apr-09	100	61,000.00	56,629.12
May-09	100	61,000.00	56,629.12
Jun-09	100	61,000.00	56,629.12
Jul-09	100	61,000.00	52,258.25
Aug-09	100	61,000.00	47,897.36
Sep-09	95.6	58,316.00	43,549.75
Oct-09	90.4	55,144.00	42,490.78
Nov-09	97	59,170.00	38,174.31
Dec-09	81	49,410.00	42,524.77
Jan-10	78.8	48,068.00	43,540.46
Feb-10	90.4	55,144.00	56,676.79
Mar-10	102	62,220.00	56,628.85
Apr-10	100	61,000.00	56,629.13
May-10	100	61,000.00	52,258.25
Jun-10	97	59,170.00	47,897.37
Jul-10	96	58,560.00	43,549.75
Aug-10	95	57,950.00	43,687.02
Sep-10	93	56,730.00	45,546.80
Oct-10	100	61,000.00	56,665.10
Nov-10	100	61,000.00	56,628.92

Table B.13: Ewen Maddock Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jul-09	95.7	15873.759	15,873.00
Aug-09	91.5	15177.105	14,930.77
Sep-09	89.4	14828.778	13,991.50
Oct-09	85.2	14132.124	13,052.23
Nov-09	82.2	13634.514	12,113.88
Dec-09	78.2	12971.034	11,179.44
Jan-10	77.2	12805.164	10,249.82
Feb-10	76.2	12639.294	10,743.53
Mar-10	104.7	17366.589	15,660.11
Apr-10	102	16918.74	15,645.44
May-10	100	16587	15,645.48
Jun-10	98.9	16404.543	15,645.48
Jul-10	96.8	16056.216	14,703.97
Aug-10	94.9	15741.063	14,974.30
Sep-10	96.8	16056.216	15,647.59
Oct-10	100	16587	15,645.48
Nov-10	100	16587	15,645.48
Dec-10	100	16587	15,645.48

Table B.14: Lake Kuruwongbah Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jul-08	79.8	11467.26	11,467.26
Aug-08	78.4	11266.08	12,778.80
Sep-08	81.1	11654.07	11,142.94
Oct-08	76.1	10935.57	12,787.13
Nov-08	68.8	9886.56	12,733.86
Dec-08	100	14370	12,735.68
Jan-09	95.1	13665.87	12,735.62
Feb-09	100	14370	12,735.62
Mar-09	90.1	12947.37	12,735.62
Apr-09	100	14370	12,735.62
May-09	95.3	13694.61	12,735.62
Jun-09	99.5	14298.15	12,735.62
Jul-09	96.4	13852.68	12,735.62
Aug-09	90.1	12947.37	11,101.24
Sep-09	86.1	12372.57	9,519.44
Oct-09	88.8	12760.56	7,981.14
Nov-09	76.3	10964.31	9,097.62
Dec-09	72.2	10375.14	7,572.41
Jan-10	70.4	10116.48	12,828.27
Feb-10	68.2	9800.34	12,732.45
Mar-10	101.9	14643.03	12,735.73
Apr-10	95.9	13780.83	12,735.62
May-10	95.9	13780.83	12,735.62
Jun-10	92	13220.4	11,101.24
Jul-10	89.4	12846.78	9,519.44
Aug-10	87	12501.9	7,981.14
Sep-10	92	13220.4	11,785.78
Oct-10	99	14226.3	12,768.14
Nov-10	100	14370	12,734.51
Dec-10	100	14370	12,735.66

Table B.15 –Macdonald Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jul-08	100	8018.00	8,018.00
Aug-08	100	8018.00	6,864.19
Sep-08	100	8018.00	5,724.17
Oct-08	100	8018.00	6,886.33
Nov-08	96.1	7705.30	5,746.21
Dec-08	100	8018.00	6,886.13
Jan-09	90.9	7288.36	6,877.88
Feb-09	100	8018.00	6,877.92
Mar-09	100	8018.00	6,877.92
Apr-09	100	8018.00	6,877.92
May-09	100	8018.00	6,877.92
Jun-09	100	8018.00	6,877.92
Jul-09	100	8018.00	6,877.92
Aug-09	105	8418.90	5,737.84
Sep-09	96.5	7737.37	4,606.04
Oct-09	90.9	7288.36	3,494.70
Nov-09	77.9	6246.02	2,420.93
Dec-09	74.5	5973.41	2,322.42
Jan-10	78.4	6286.11	6,405.82
Feb-10	88	7055.84	6,880.11
Mar-10	100	8018.00	6,877.91
Apr-10	100	8018.00	6,877.92
May-10	100	8018.00	6,877.92
Jun-10	100	8018.00	6,877.92
Jul-10	100	8018.00	5,737.84
Aug-10	100	8018.00	6,265.79
Sep-10	100	8018.00	6,881.39
Oct-10	100	8018.00	6,877.90
Nov-10	100	8018.00	6,877.92
Dec-10	100	8018.00	6,877.92

Table B.16: Leslie Harrison Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jul-08	99.1	24644.19	24,644.19
Aug-08	97	24121.96	23,880.08
Sep-08	69.8	17357.86	22,908.02
Oct-08	93.9	23351.05	22,697.39
Nov-08	91.6	22779.09	21,749.89
Dec-08	99.6	24768.53	23,937.90
Jan-09	95.2	23674.34	23,894.74
Feb-09	92.3	22953.16	23,749.75
Mar-09	97.6	24271.17	23,898.65
Apr-09	95.2	23674.34	23,724.87
May-09	100	24868.00	23,899.17
Jun-09	100	24868.00	23,895.55
Jul-09	100	24868.00	23,895.62
Aug-09	96.3	23947.88	22,923.24
Sep-09	93.1	23152.11	21,971.06
Oct-09	91.7	22803.96	21,037.16
Nov-09	85.3	21212.40	20,805.72
Dec-09	80.4	19993.87	19,891.82
Jan-10	82.5	20516.10	20,878.06
Feb-10	82	20391.76	19,962.92
Mar-10	99.6	24768.53	21,138.42
Apr-10	97.8	24320.90	22,703.53
May-10	97.6	24271.17	22,899.09
Jun-10	95.8	23823.54	22,777.39
Jul-10	92.4	22978.03	21,828.23
Aug-10	96.2	23923.02	20,896.78
Sep-10	94	23375.92	21,576.03
Oct-10	94	23375.92	21,643.32
Nov-10	97	24121.96	23,633.03
Dec-10	98	24370.64	23,370.81

Table B.17: Maroon Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jan-08	51.2	23203.33	23,203.33
Feb-08	61.8	28007.14	26,369.16
Mar-08	62.6	28369.69	28,469.80
Apr-08	62.4	28279.06	28,958.02
May-08	62	28097.78	28,130.74
Jun-08	62	28097.78	27,305.32
Jul-08	62	28097.78	26,481.76
Aug-08	62	28097.78	25,664.34
Sep-08	62	28097.78	24,853.73
Oct-08	61	27644.59	24,049.88
Nov-08	59.6	27010.12	23,252.73
Dec-08	65.1	29502.67	26,962.99
Jan-09	65.7	29774.58	29,440.27
Feb-09	68	30816.92	31,533.28
Mar-09	68	30816.92	32,023.10
Apr-09	69	31270.11	31,188.55
May-09	73	33082.87	32,009.87
Jun-09	82.2	37252.22	33,757.53
Jul-09	85.4	38702.43	34,248.22
Aug-09	85.3	38657.11	33,405.82
Sep-09	84.3	38203.92	32,566.39
Oct-09	81.4	36889.67	31,729.93
Nov-09	81	36708.39	30,896.41
Dec-09	77.8	35258.18	31,536.07
Jan-10	79.8	36164.56	35,309.77
Feb-10	83.7	37932.00	35,716.54
Mar-10	90.4	40968.38	38,986.00
Apr-10	90	40787.10	40,182.35
May-10	90	40787.10	39,332.90
Jun-10	89	40333.91	39,751.20
Jul-10	88	39880.72	38,901.75
Aug-10	89	40333.91	38,052.30
Sep-10	89	40333.91	38,326.45
Oct-10	92	41693.48	39,382.87
Nov-10	99	44865.81	41,325.46
Dec-10	100	45319.00	43,180.07

Table B 18: Moogerah Storage Actual vs Simulated

Month	Actual storage (%)	Actual storage volume (ML)	Simulated storage volume (ML)
Jan-08	17.5	14,658.88	14,659.00
Feb-08	49.6	41,547.44	18,025.23
Mar-08	49.1	41,128.62	23,862.13
Apr-08	47.6	39,872.14	25,075.73
May-08	45.8	38,364.37	24,747.27
Jun-08	44.3	37,107.90	24,425.19
Jul-08	42.9	35,935.19	25,267.61
Aug-08	41.5	34,762.48	26,646.38
Sep-08	40.1	33,589.77	26,297.92
Oct-08	38.1	31,914.47	25,953.81
Nov-08	36.3	30,406.70	26,931.84
Dec-08	47	39,369.55	33,424.37
Jan-09	47	39,369.55	34,853.98
Feb-09	48.4	40,542.26	37,771.73
Mar-09	47.9	40,123.44	39,648.30
Apr-09	47.5	39,788.38	39,055.96
May-09	47.2	39,537.08	41,044.96
Jun-09	50.1	41,966.27	43,995.50
Jul-09	49.4	41,379.91	43,368.90
Aug-09	50.6	42,385.09	42,746.94
Sep-09	48.6	40,709.79	42,129.59
Oct-09	45.1	37,778.02	41,516.80
Nov-09	44	36,856.60	40,908.90
Dec-09	40.8	34,176.12	42,782.13
Jan-10	44.6	37,359.19	46,491.96
Feb-10	54.4	45,568.16	47,935.36
Mar-10	65	54,447.25	52,945.38
Apr-10	65.8	55,117.37	54,887.78
May-10	64.9	54,363.49	54,171.96
Jun-10	64.2	53,777.13	54,675.72
Jul-10	63.2	52,939.48	53,961.86
Aug-10	62.2	52,101.83	53,254.61
Sep-10	62	51,934.30	53,762.31
Oct-10	68	56,960.20	55,496.50
Nov-10	80	67,012.00	57,620.49
Dec-10	100	83,765.00	60,837.45

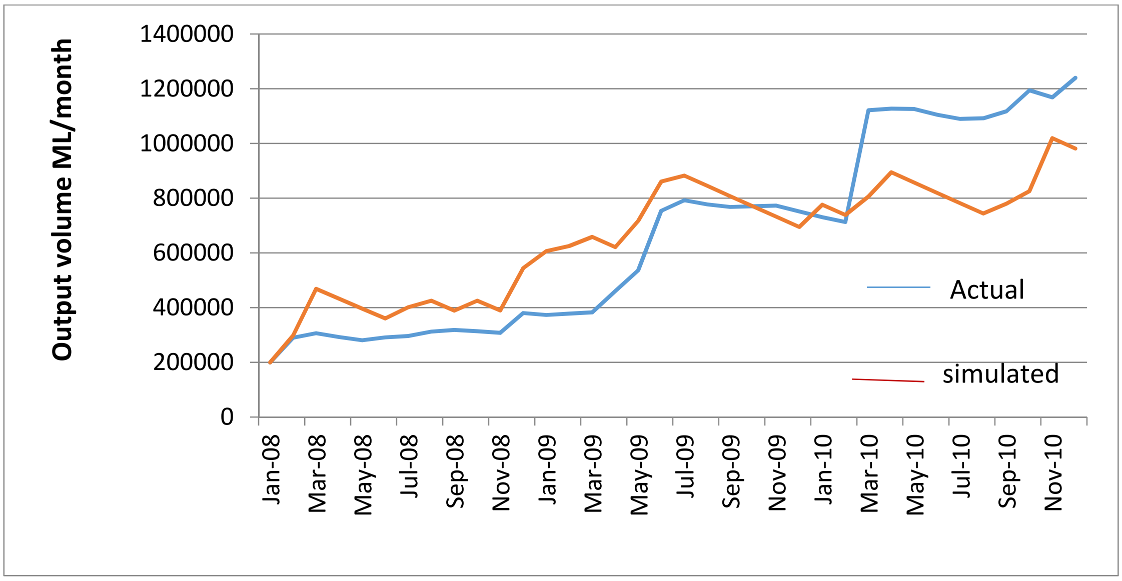

Figure B 9: Comparison of actual and simulated storage volumes –Wivenhoe

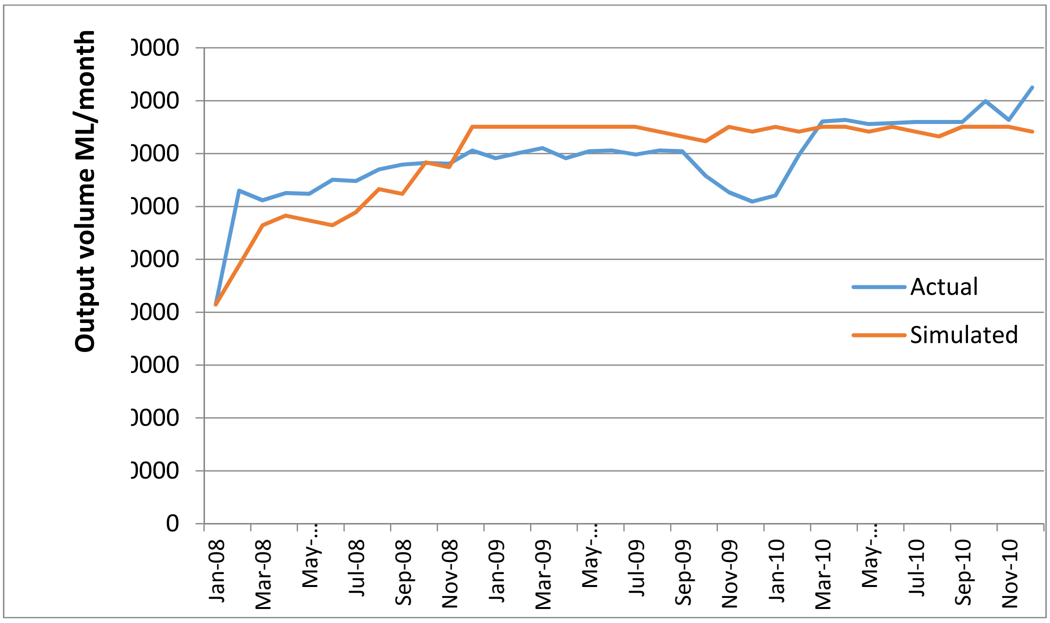

Figure B 10: Comparison of actual and simulated storage volumes –Somerset

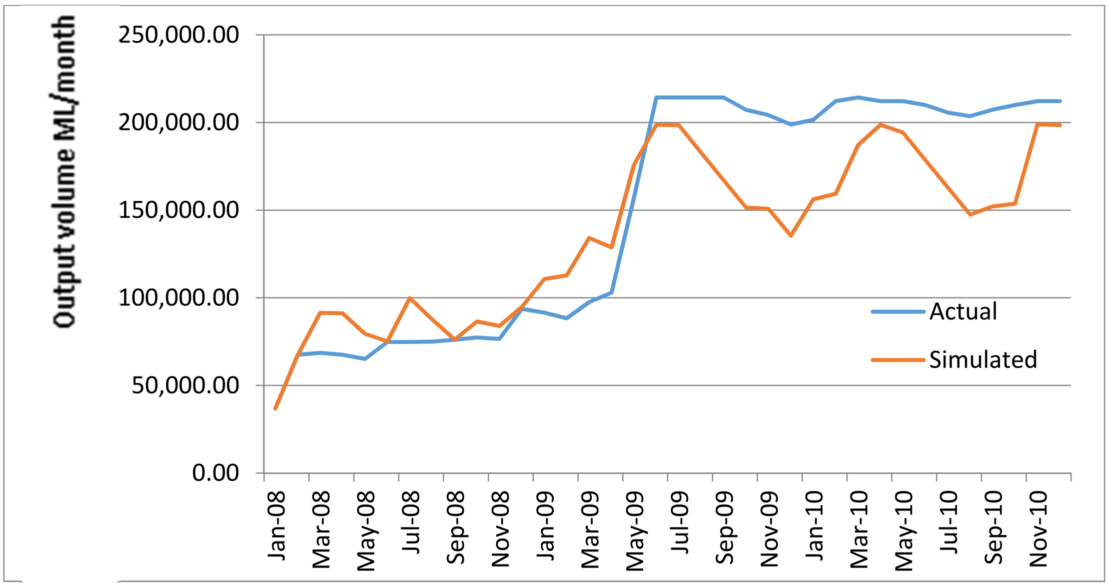

Figure B 11: Comparison of actual and simulated storage volumes –North Pine

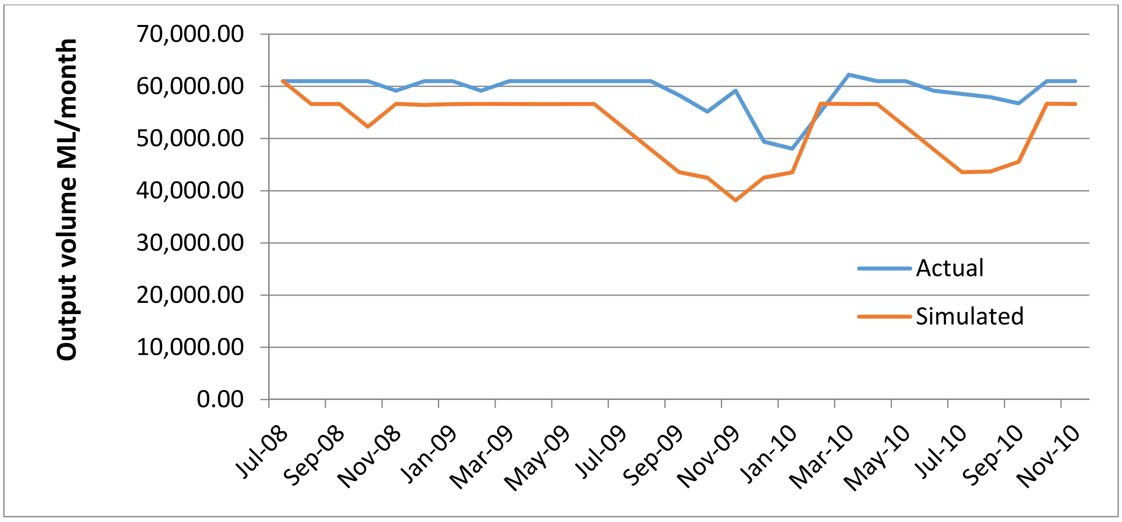

Figure B 12: Comparison of actual and simulated storage volumes –Baroon Pocket

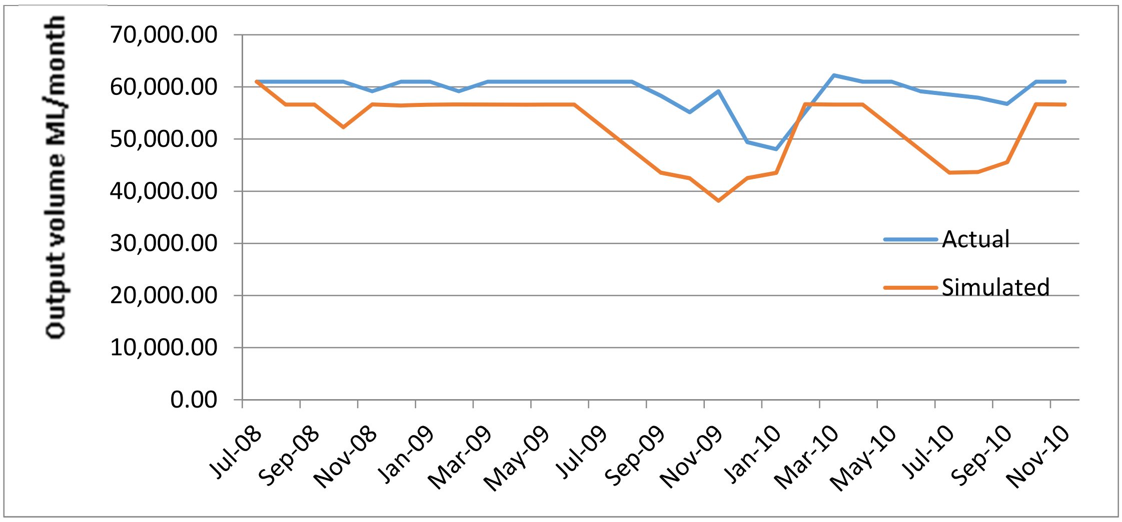

Figure B 13: Comparison of actual and simulated storage volumes –Ewen Maddock

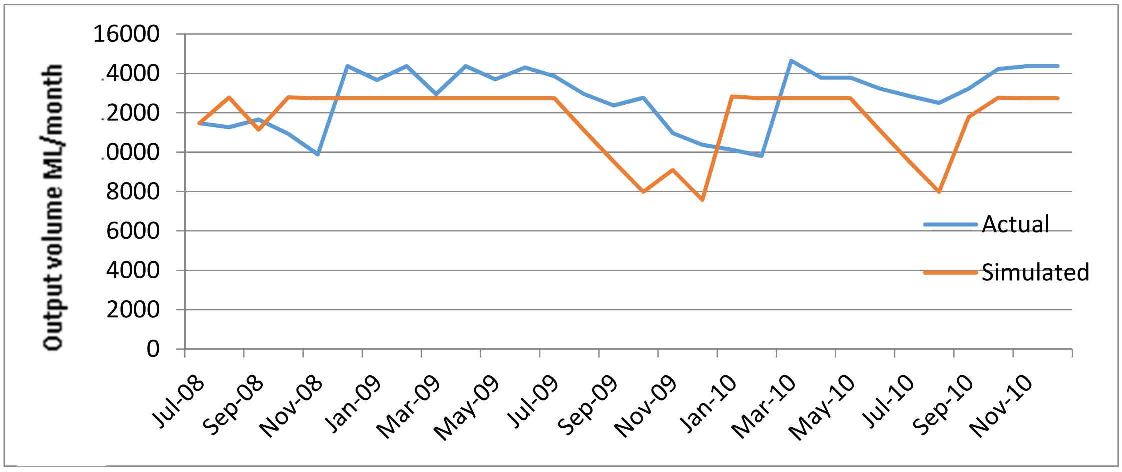

Figure B 14: Comparison of actual and simulated storage volumes – Kuruwongbah

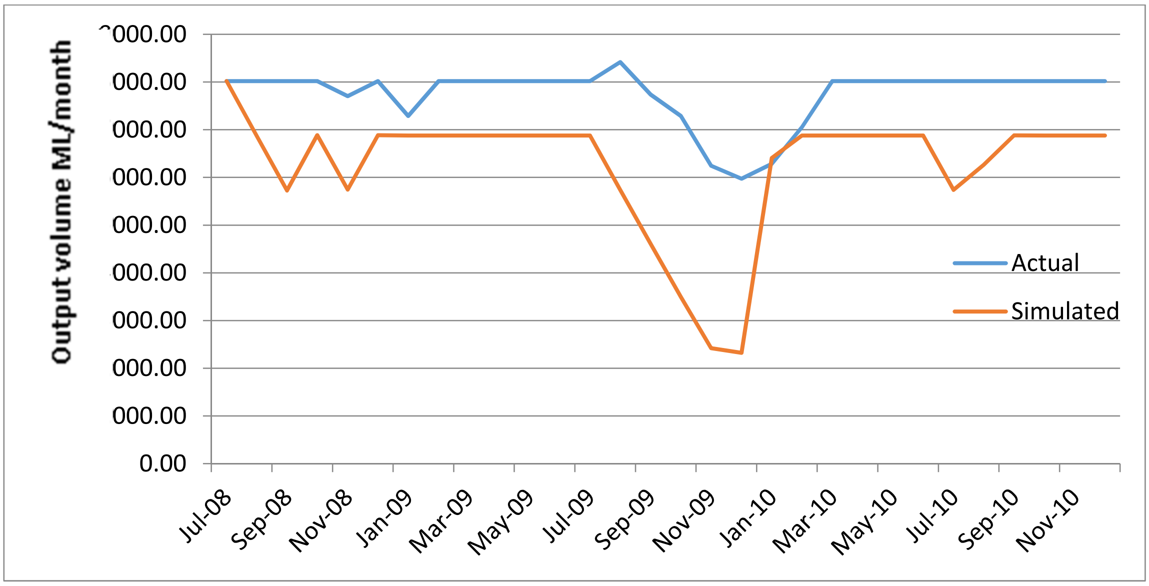

Figure B 15: Comparison of actual and simulated storage volumes –Lake Macdonald

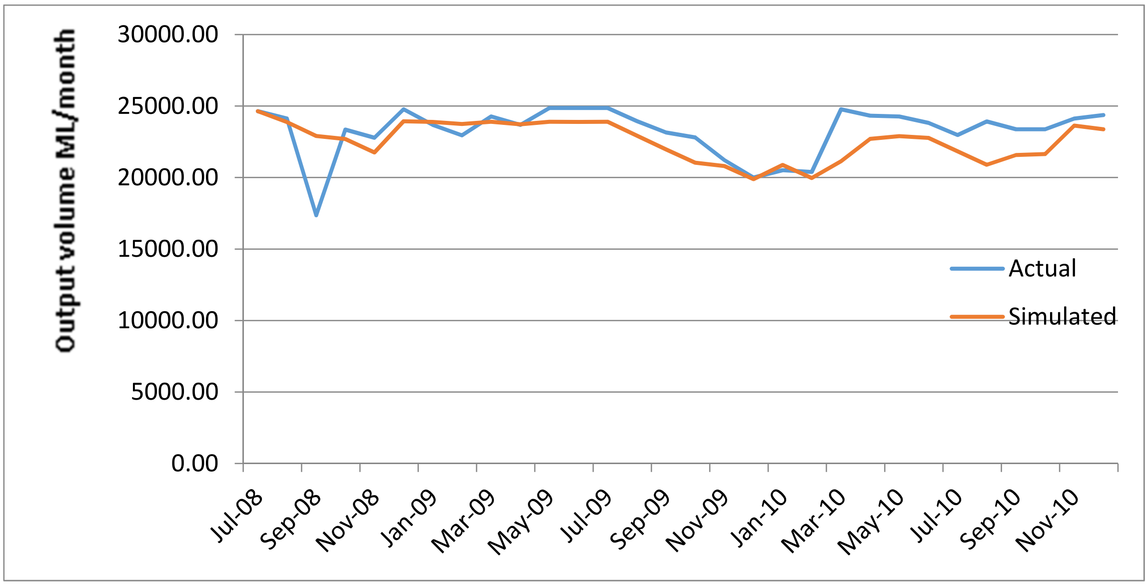

Figure B 16: Comparison of actual and simulated storage volumes –Leslie Harrison

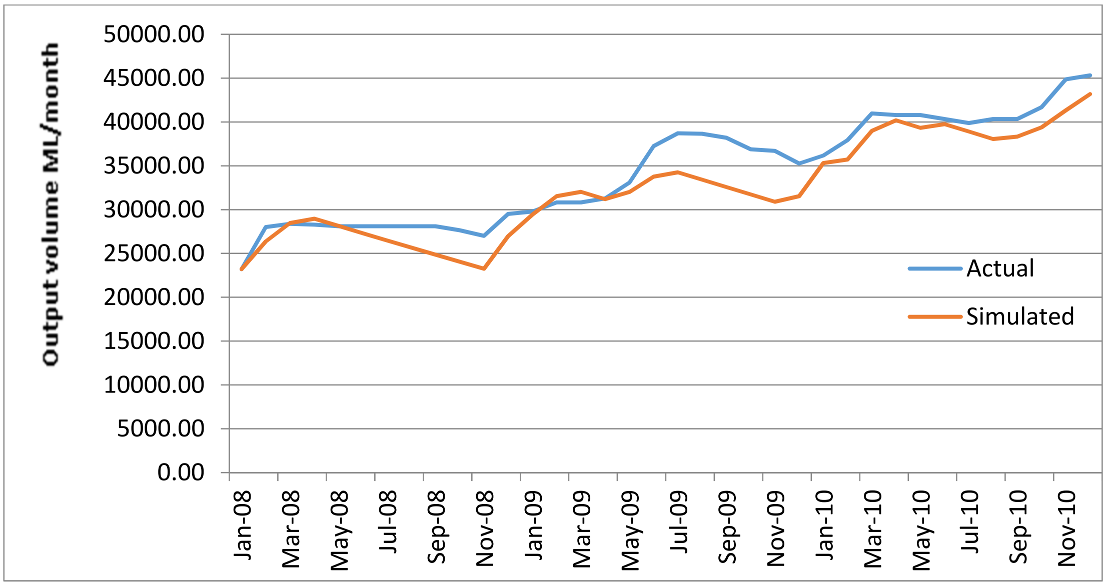

Figure B 17: Comparison of actual and simulated storage volumes –Maroon

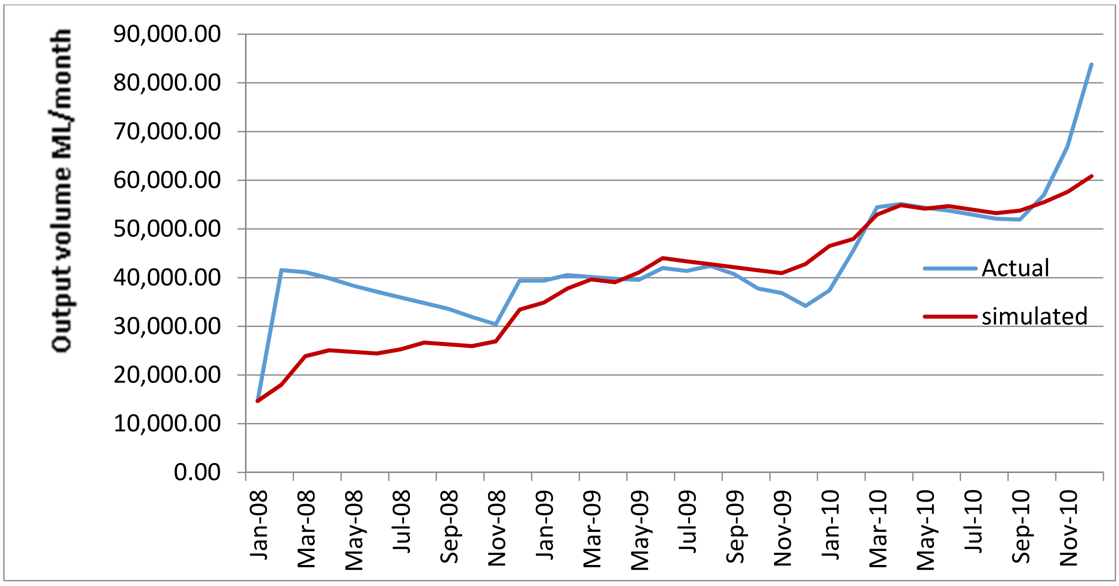

Figure B 18: Comparison of actual and simulated storage volumes –Moogarah

Appendix C

System behavior under different scenarios

Table C.1: Minimum output for each month (ML) from 100 simulations for different rainfall conditions- Reservoir storage 0%

Month	Rainfall 100% of average	Rainfall 90% of average	Rainfall 70% of average	Rainfall 60% of average	Rainfall 50% of average	Rainfall 40% of average	Rainfall 20% of average
1	0	0	0	0	0	0	0
2	1170	1170	1170	1170	1170	1170	4920
3	5528	5468	4920	4920	4920	4920	4530
4	7536.5	8357.5	6988.5	6076	6380.5	5832.5	4920
5	13026.5	12378.5	8297.5	6988.5	6380.5	6380.5	4920
6	13595.5	12378.5	8926.5	6988.5	6988.5	5468	4920
7	13133.5	13026.5	8357.5	6988.5	6380.5	5468	4920
8	13574.5	12926.5	8357.5	7636.5	6988.5	4920	4920
9	13495.5	12378.5	8357.5	6988.5	6380.5	4920	4920
10	12926.5	12378.5	8357.5	6988.5	6380.5	5468	4920
11	13026.5	8905.5	8357.5	8357.5	6380.5	5468	4920
12	20174.5	13681.5	8397.5	8464.5	6988.5	5468	4920
13	22203.5	16260.5	13595.5	8926.5	6380.5	5528	4920
14	28155.5	28155.5	21634.5	21555.5	11557.5	6076	4920
15	28803.5	28216	20986.5	15605.5	14957.5	7749.5	4920
16	28803.5	28058	21634.5	20438.5	13574.5	8926.5	5468
17	28291	28262.5	22203.5	22203.5	13033.5	11466	4920
18	28910.5	28262.5	22203.5	20174.5	13681.5	8357.5	4920
19	28957	28262.5	22203.5	20174.5	9660.5	8905.5	4920
20	28910.5	28155.5	21655.5	13026.5	12226.5	8357.5	4920
21	28803.5	28155.5	21634.5	10122.5	8205.5	6949.5	4920
22	28910.5	26255.5	17613.5	10122.5	8093	7749.5	4920
23	22310.5	21741.5	17065.5	15596.5	7636.5	6988.5	4920
24	28910.5	22203.5	16165.5	12166.5	9005.5	6076	4920
25	28910.5	28910.5	20195.5	13702.5	16181	6645	4920
26	52973	52973	28341.5	20850.5	21555.5	6988.5	4920
27	52973	52973	28341.5	17741.5	10229.5	11314	4920
28	52973	52973	28803.5	22203.5	17641.5	11557.5	5468
29	52973	30883	28803.5	22203.5	20174.5	11657.5	5468
30	32855.5	47556.5	28255.5	21662.5	16272.5	11657.5	5468
31	28910.5	32198	22310.5	21655.5	10122.5	7636.5	5468
32	32855.5	28910.5	22310.5	14143.5	10122.5	6837	4920
33	28910.5	27570.5	17741.5	14143.5	9005.5	6988.5	4920

Table C1- Continued

Month	Rainfall 100% of average	Rainfall 90% of average	Rainfall 70% of average	Rainfall 60% of average	Rainfall 50% of average	Rainfall 40% of average	Rainfall 20% of average
34	28910.5	28910.5	28803.5	13595.5	9553.5	7557.5	4920
35	28910.5	28910.5	17741.5	17613.5	8184.5	6988.5	4920
36	28910.5	28910.5	17741.5	20195.5	12947.5	8357.5	4920
37	28910.5	28910.5	22310.5	20941.5	10229.5	6076	4920
38	28910.5	37458	28910.5	22310.5	13338	12774.5	4920
39	52973	52973	28655.5	27541.5	15917	8357.5	4920
40	52973	30225.5	28856.5	26972.5	18009.5	10229.5	5468
41	52973	52973	28910.5	23625.5	21634.5	12166.5	5832.5
42	31540.5	29568	27541.5	18289.5	18852.5	8905.5	5832.5
43	28910.5	28910.5	27541.5	18289.5	17613.5	13026.5	5468
44	28910.5	32855.5	24889.5	18289.5	17065.5	9005.5	4920
45	28910.5	28910.5	20941.5	20941.5	13595.5	7636.5	4920
46	28910.5	28910.5	22310.5	13702.5	11685.5	7636.5	4920
47	28910.5	28910.5	22310.5	20372.5	13595.5	7557.5	4920
48	28910.5	28910.5	22310.5	20281	13595.5	7557.5	4920
49	52973	28910.5	22310.5	21741.5	9033.5	7557.5	4920
50	52973	52973	28910.5	22310.5	14143.5	12226.5	4920
51	52973	52973	28910.5	22310.5	13595.5	12887.5	4920
52	52973	52973	27519.5	22310.5	21508	12887.5	5468
53	52973	52973	28910.5	22310.5	20850.5	12887.5	5468
54	52973	31540.5	22310.5	20393.5	20850.5	16417.5	5468
55	52973	28910.5	22310.5	22310.5	14250.5	17065.5	4920
56	52973	28910.5	27541.5	14250.5	12333.5	11578.5	4920
57	52973	28910.5	27541.5	14250.5	12233.5	7557.5	4920
58	52973	28910.5	27541.5	14250.5	12333.5	7557.5	4920
59	52973	28910.5	23625.5	18289.5	12333.5	7636.5	4920

Table C.2: Minimum output for each month (ML) from 100 simulations for different rainfall conditions- Reservoir storage 50%

Month	Rainfall 70%	Rainfall 60%	Rainfall 50%	Rainfall 40%	Rainfall 20%	Threshold
1	52973	52973	52973	52973	52973	12000
2	52973	52973	52973	52973	52973	12000
3	52973	52973	52973	52973	52973	12000
4	52973	52973	52973	52973	52973	12000
5	52973	52973	52973	52973	52973	12000
6	52973	52973	52973	52973	51697.5	12000
7	52973	52973	52897	52973	52811	12000
8	52973	52973	52185.5	52973	49454	12000
9	52973	52973	48627	46157	47830	12000
10	50848.5	50921.5	46814.5	45390.5	41425	12000
11	52948	49411.5	48841	43451	42854	12000
12	52973	49411.5	46759.5	43282	41875.5	12000
13	47663	24351	18289.5	14926	43322	12000
14	52973	28910.5	28910.5	10229.5	13989	12000
15	52973	28910.5	22310.5	16920.5	7948	12000
16	52973	26853	22310.5	18801.5	8312.5	12000
17	35023	28910.5	22310.5	16920.5	7704.5	12000
18	28910.5	28910.5	22310.5	14250.5	6792	12000
19	28910.5	21769	22310.5	14250.5	6792	12000
20	28910.5	22310.5	18947	8860.5	6144	12000
21	28910.5	22310.5	16920.5	7400	6144	12000
22	28910.5	22310.5	16920.5	8312.5	6144	12000
23	28910.5	18923	16920.5	9681.5	6144	12000
24	22968	20029	16920.5	8312.5	5596	12000
25	28910.5	17377	16920.5	8860.5	5596	12000
26	28910.5	22310.5	14250.5	15460.5	6144	12000
27	28910.5	22310.5	18289.5	8860.5	5575	12000
28	28910.5	28910.5	20941.5	17741.5	6831	12000
29	28910.5	22310.5	20941.5	14250.5	6144	12000
30	28910.5	22310.5	20941.5	14250.5	6144	12000
31	24940.5	22310.5	18289.5	9581.5	5575	12000
32	22310.5	22310.5	14250.5	9581.5	5575	12000
33	22310.5	18289.5	10229.5	8860.5	5575	12000
34	22310.5	17741.5	10229.5	8860.5	5027	12000
35	22310.5	17741.5	8860.5	8312.5	5027	12000

Table C 2: Continued

Month	Rainfall 70%	Rainfall 60%	Rainfall 50%	Rainfall 40%	Rainfall 20%	Threshold
36	28910.5	20941.5	15917	8860.5	5027	12000
37	22310.5	20941.5	16008	8312.5	5027	12000
38	28910.5	22310.5	18289.5	12333.5	5027	12000
39	28910.5	22310.5	13702.5	14250.5	5575	12000
40	28910.5	23625.5	18947	13681.5	5575	12000
41	28910.5	22310.5	21762.5	13702.5	5575	12000
42	22310.5	21762.5	9681.5	13702.5	5575	12000
43	28910.5	21762.5	14926	9681.5	5575	12000
44	22310.5	16375.5	12333.5	9681.5	5027	12000
45	22310.5	18289.5	8312.5	8312.5	5027	12000
46	21090.5	16372.5	13702.5	8312.5	5575	12000
47	22310.5	18289.5	13702.5	8312.5	5027	12000
48	28910.5	17741.5	13702.5	7743.5	5027	12000
49	28910.5	18289.5	16372.5	8312.5	5027	12000
50	22310.5	22310.5	20393.5	10229.5	5027	12000
51	28910.5	22310.5	20393.5	14250.5	5027	12000
52	28910.5	22310.5	17741.5	10279	5027	12000
53	27485	22310.5	18289.5	12333.5	5575	12000
54	22310.5	21526	18289.5	12333.5	5027	12000
55	22310.5	18289.5	17741.5	7664.5	5027	12000
56	22310.5	22310.5	14926	7664.5	5027	12000
57	22310.5	18289.5	17741.5	7664.5	5027	12000
58	22310.5	18289.5	16372.5	8312.5	4920	12000
59	20941.5	18289.5	16372.5	7704.5	4920	12000

16,375.5 - Minimum output for 60% of average rainfall for 50% storage

Table C.3: Minimum output for each month (ML) from 100 simulations for different rainfall conditions- Reservoir storage 100%

Month	Rainfall 70%	Rainfall 60%	Rainfall 50%	Rainfall 40%	Rainfall 20%	Threshold
1	52973	52973	52973	52973	52973	12000
2	52973	52973	52973	52973	52973	12000
3	52973	52973	52973	52973	52973	12000
4	52973	52973	52973	52973	52973	12000
5	52973	52973	52973	52973	52973	12000
6	52973	52973	52973	52973	52973	12000
7	52973	52973	52973	52973	52973	12000
8	52973	52973	52973	52973	52973	12000
9	52973	52973	52973	52973	52973	12000
10	52973	52973	52973	52973	52973	12000
11	52973	52973	52973	52973	52973	12000
12	52973	52973	52973	52973	52448.5	12000
13	52973	52973	52973	52973	51737	12000
14	52973	52973	52973	52973	47917.5	12000
15	52973	52973	52973	52973	48574.5	12000
16	52973	52973	52973	52973	49199	12000
17	52973	52973	52973	51258	48521	12000
18	52973	52973	52973	51915.5	43490.5	12000
19	52973	52973	48870	50377.5	41230	12000
20	52973	52973	50440.5	49123.5	42483.5	12000
21	52973	52973	50780.5	46759.5	43870	12000
22	52973	52973	46759.5	43713.5	43870	12000
23	52973	52413	46759.5	41335.5	43322	12000
24	52973	48295.5	45390.5	42027	43322	12000
25	52973	48953	45390.5	44478	43870	12000
26	52973	52973	49411.5	45390.5	43870	12000
27	52973	52973	37948	18289.5	15400	12000
28	52973	52973	28910.5	31540.5	15400	12000
29	52973	52973	48732	21545	14993	12000
30	52973	52240.5	29568	18289.5	8312.5	12000
31	52973	50780.5	26094.5	16920.5	7400	12000
32	52973	43516.5	22310.5	16920.5	7704.5	12000
33	52973	28910.5	18998	16920.5	7704.5	12000
34	52973	28910.5	20941.5	14926	6792	12000
35	52973	28910.5	18289.5	16008	6792	12000

Table C3: Continued

Month	Rainfall 70%	Rainfall 60%	Rainfall 50%	Rainfall 40%	Rainfall 20%	Threshold
36	49585.5	27541.5	21398	16008	6792	12000
37	50243	27541.5	17593	16920.5	6792	12000
38	52973	28910.5	22310.5	18289.5	6792	12000
39	52973	22968	21344	16372.5	6792	12000
40	52973	29568	21398	18289.5	7704.5	12000
41	52973	37603	22310.5	16920.5	7400	12000
42	52973	28910.5	22310.5	16372.5	6792	12000
43	52973	27541.5	22310.5	16372.5	6792	12000
44	52775.5	28910.5	18289.5	16008	6244	12000
45	28910.5	21762.5	16920.5	16372.5	6244	12000
46	25620.5	21762.5	14926	16008	6244	12000
47	26278	21628	16372.5	16312.5	6244	12000
48	28910.5	22310.5	16372.5	15460	6244	12000
49	21526	20080.5	16829	16372.5	6244	12000
50	28910.5	28910.5	18289.5	17741.5	6792	12000
51	28910.5	22310.5	16920.5	17741.5	6144	12000
52	28910.5	28910.5	16920.5	17681.5	6792	12000
53	28910.5	22310.5	20941.5	17851	6144	12000
54	28910.5	22310.5	20941.5	16372.5	6792	12000
55	28910.5	22310.5	19518.5	16372.5	6792	12000
56	28910.5	22310.5	20941.5	15764.5	6752	12000
57	28910.5	20850	17741.5	16008	5575	12000
58	22310.5	20941.5	16829	16312.5	6144	12000
59	28910.5	20941.5	16372.5	15460	5575	12000

14,926 - Minimum output (ML) for 40% of average rainfall for 100% storage

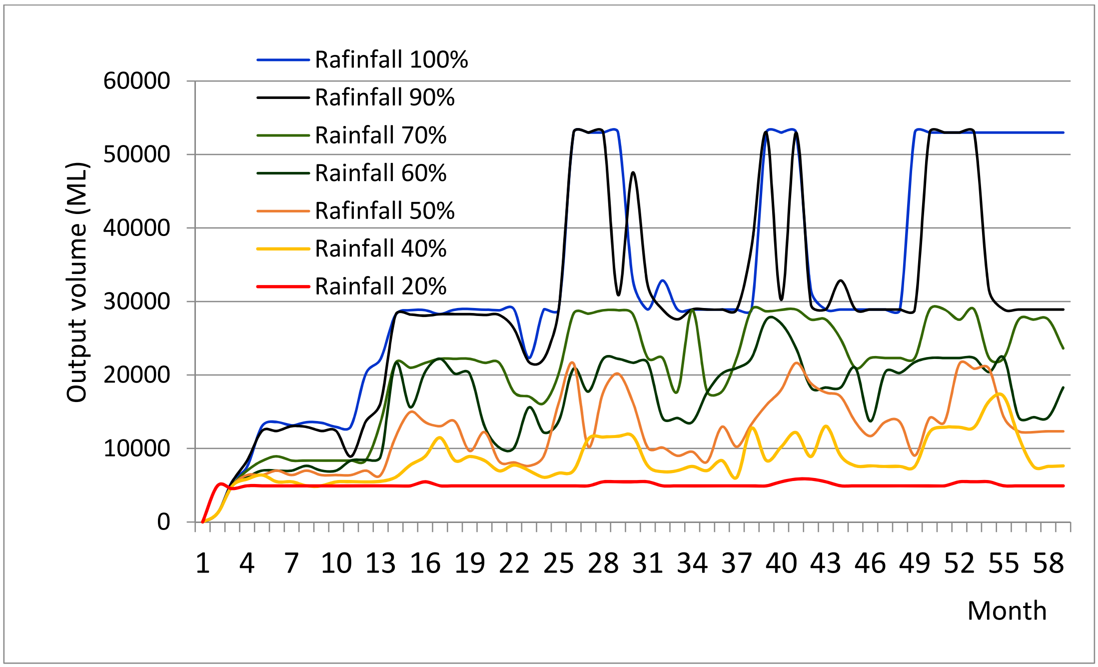

Figure C 1- Worst case scenario system behaviour (minimum output for each month) under different rainfall conditions (simulated results SEQ Water Grid for 0% storage)

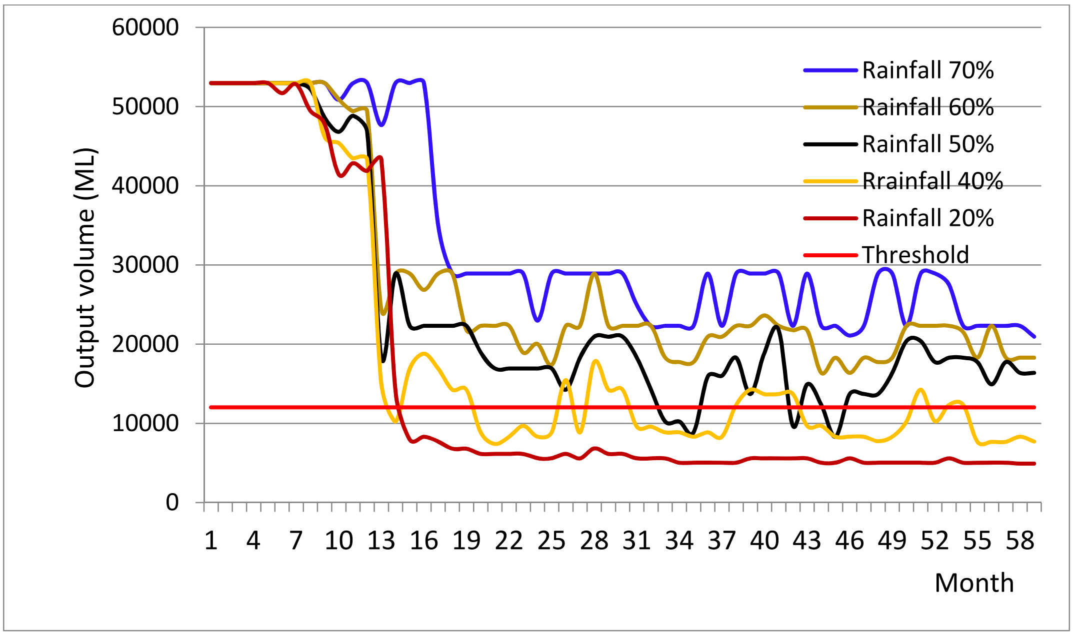

Figure C 2- Worst case scenario system behaviour (minimum output for each month) under different rainfall conditions with reference to the failure threshold (simulated results for SEQ Water Grid for 50% storage)

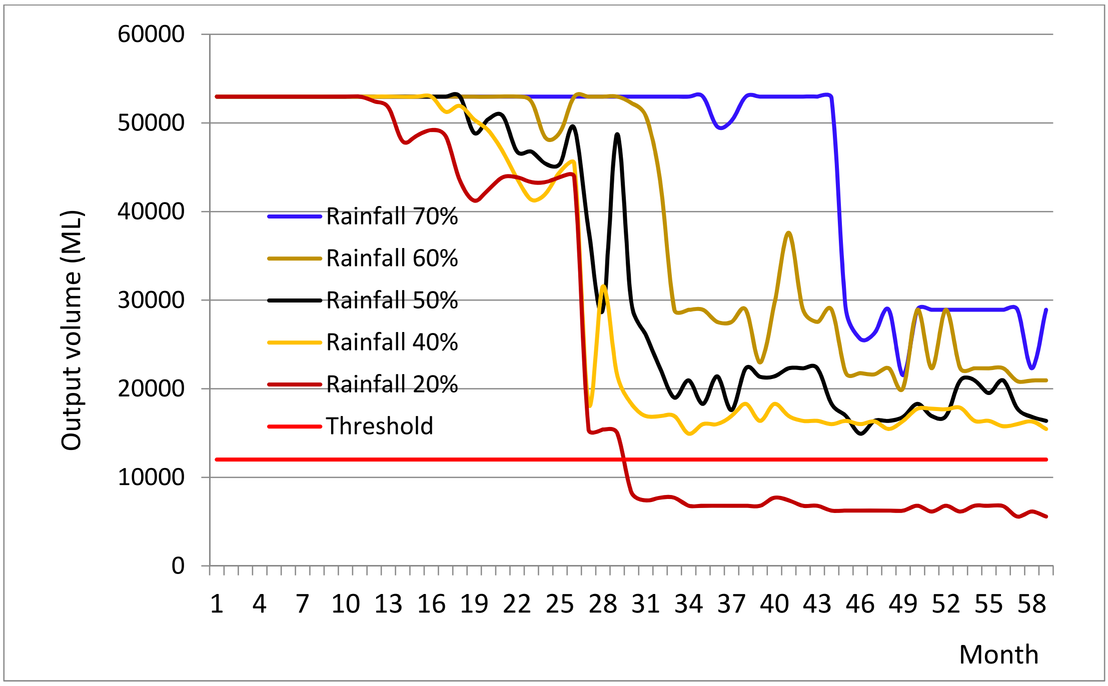

Figure C 3- Worst case scenario system behaviour (minimum output for each month) for different rainfall conditions with reference to the failure threshold (simulated results for SEQ Water Grid for 100% storage)

Table C.4: Minimum output for each month (ML) –Simulated values for drought conditions for different storages.

month	0% storage		50% storage		100% storage
	6 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)	6 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)
1	0	0	52973	52973	52973
2	4920	4920	52973	52973	52973
3	4530	4530	52973	52973	52973
4	4500	4500	52973	52973	52973
5	4500	4500	52973	52973	52973
6	4500	4500	51416.5	51416.5	52973
7	4500	4500	50658	50658	52973
8	4500	4500	50658	50658	52973
9	4920	4500	44478	44058	52973
10	4920	4500	44478	44058	52366.5
11	5832.5	4500	43870	43450	52973
12	6380.5	4500	47417	42902	52635
13	7993	4500	27541.5	6372	52973
14	20095.5	4500	52973	5824	48614
15	27038.5	6380.5	51183	18782	52973
16	28155.5	8866.5	50780.5	22310.5	52973
17	28341.5	12378.5	30883	22310.5	52973
18	28803.5	12926.5	28910.5	50780.5	52973
19	27533.5	13495.5	28910.5	30225.5	52973
20	27686.5	19487.5	28910.5	27651	47468
21	28255.5	12926.5	28910.5	21762.5	50780.5
22	22203.5	14143.5	28910.5	21762.5	48783
23	24320.5	20195.5	22310.5	20850.5	50577.5
24	28803.5	20743.5	30753	28910.5	48729
25	28910.5	21762.5	28910.5	28362.5	50780.5
26	52973	28262.5	52973	52973	52973
27	52973	28910.5	52973	52095.5	52973
28	52973	28910.5	52973	52973	52973
29	30883	28910.5	31540.5	52973	52973
30	52973	28910.5	28910.5	52973	52973
31	32198	28910.5	28910.5	52973	52973

Table C4-Continued

month	0% storage		50% storage		100% storage
	6 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)	6 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)	12 months drought (min. output of each month ML/month)
32	28910.5	28910.5	28910.5	52973	48783
33	28910.5	28910.5	28910.5	38773	50780.5
34	28910.5	28910.5	22310.5	28910.5	49160.5
35	28910.5	28910.5	28910.5	28910.5	50780.5
36	50780.5	28910.5	44033	28910.5	50780.5
37	50780.5	28655.5	52973	52973	52973
38	52973	52973	52973	52973	52973
39	52973	52973	52973	52973	52973
40	52973	30225.5	52973	52973	52973
41	52973	28910.5	52973	52973	52973
42	52973	52973	52973	52973	52973
43	52973	29568	52973	52973	52973
44	52973	28910.5	52973	52973	52973
45	34828	28910.5	34170.5	52973	52973
46	28910.5	28910.5	49950.5	34828	52973
47	28910.5	28910.5	52973	28910.5	41908.5
48	28910.5	28910.5	52973	49950.5	28910.5
49	52973	28910.5	52973	28910.5	28910.5
50	52973	28910.5	52973	52973	52973
51	52973	52973	52973	52973	52973
52	52973	52973	52973	52973	52973
53	52973	52973	52973	52973	52973
54	52973	52973	52973	52973	52973
55	52973	52973	52973	52973	52973
56	52973	32855.5	52973	52973	52973
57	52973	28910.5	52973	52973	52973
58	52973	28910.5	52973	52973	52973
59	52973	28910.5	52973	52973	52973

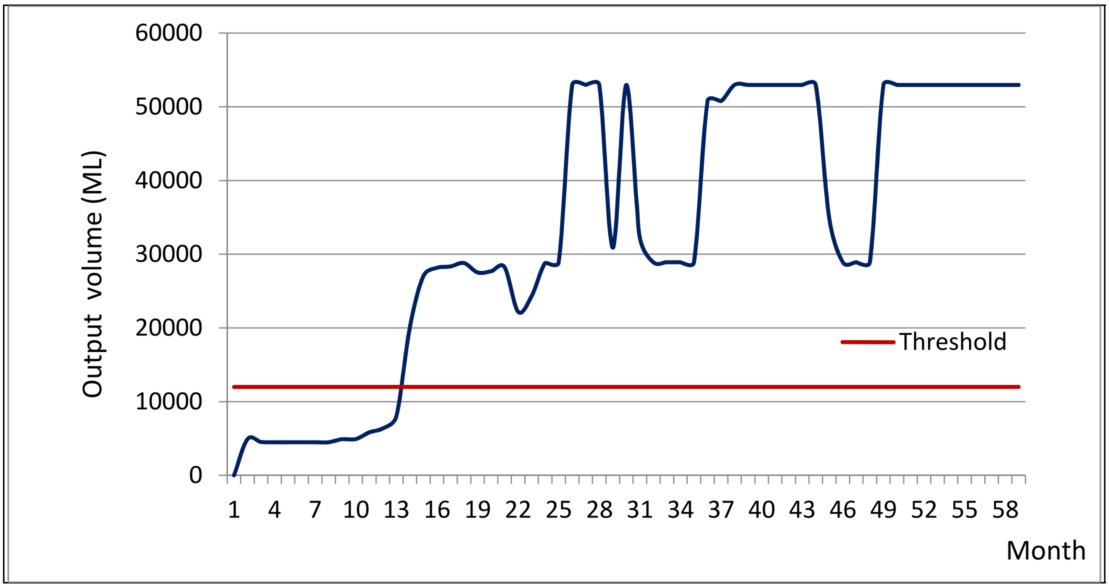

Figure C 4 - Worst case scenario system behaviour (minimum output for each month) for six month low rainfall period (simulated results for SEQ Water Grid for 0% storage)

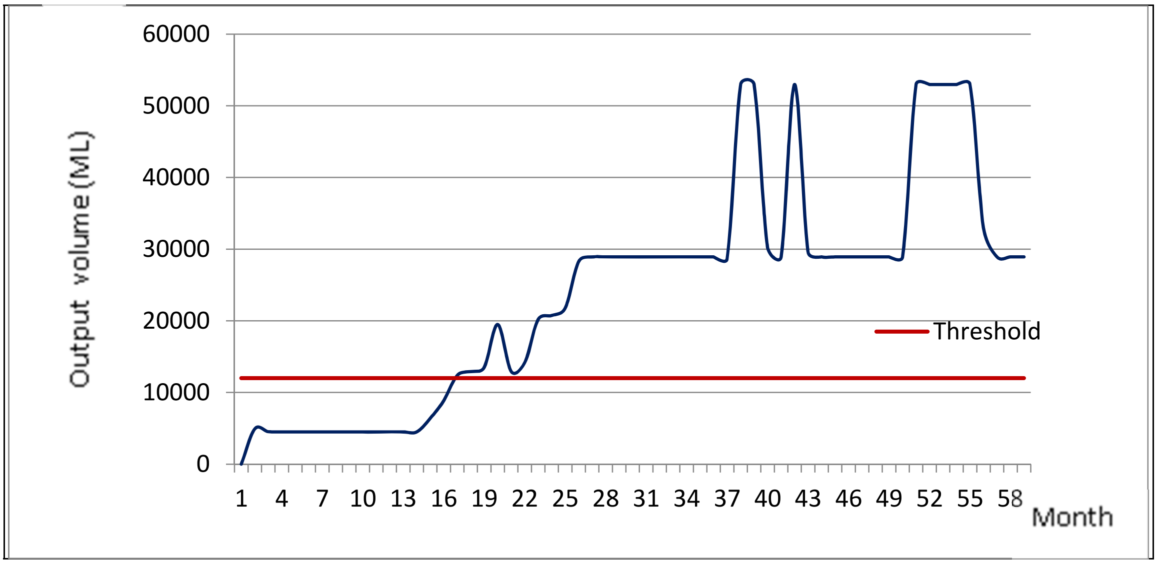

Figure C 5 - Worst case scenarios system behaviour (minimum output for each month) for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 0% initial storage)

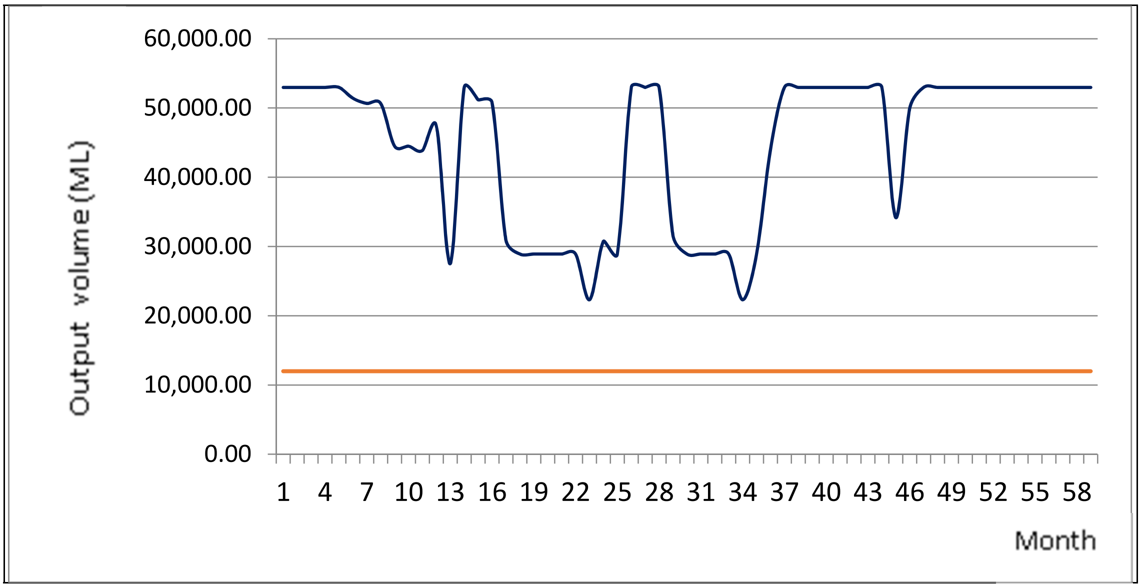

Figure C 6 - Worst case scenario system behaviour (minimum output for each month) for six month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 50% initial storage)

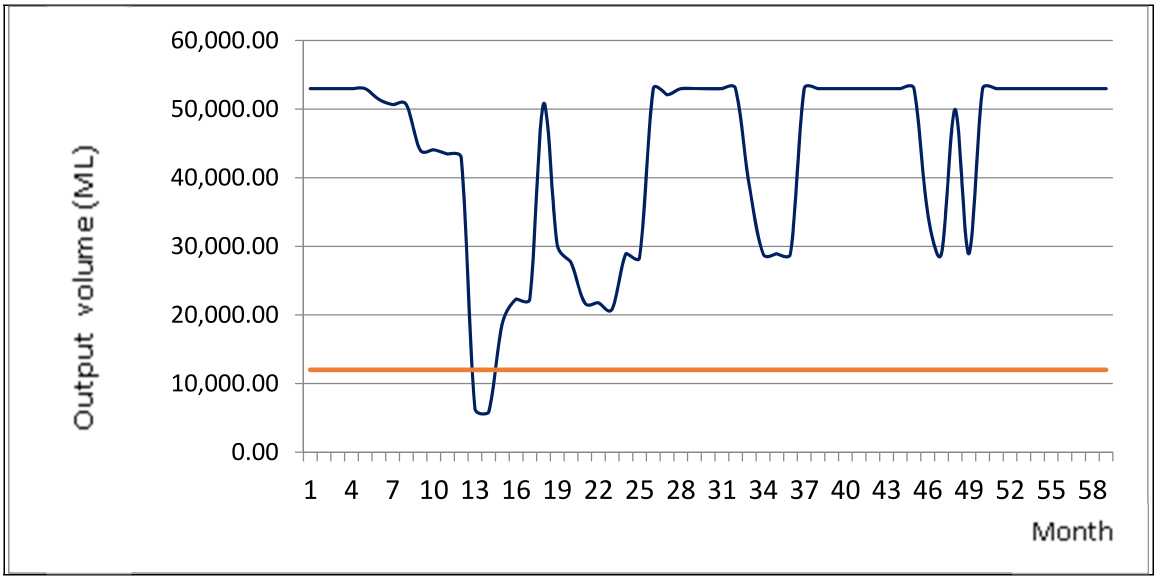

Figure C 7 – Worst case scenario system behaviour for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 50% initial storage)

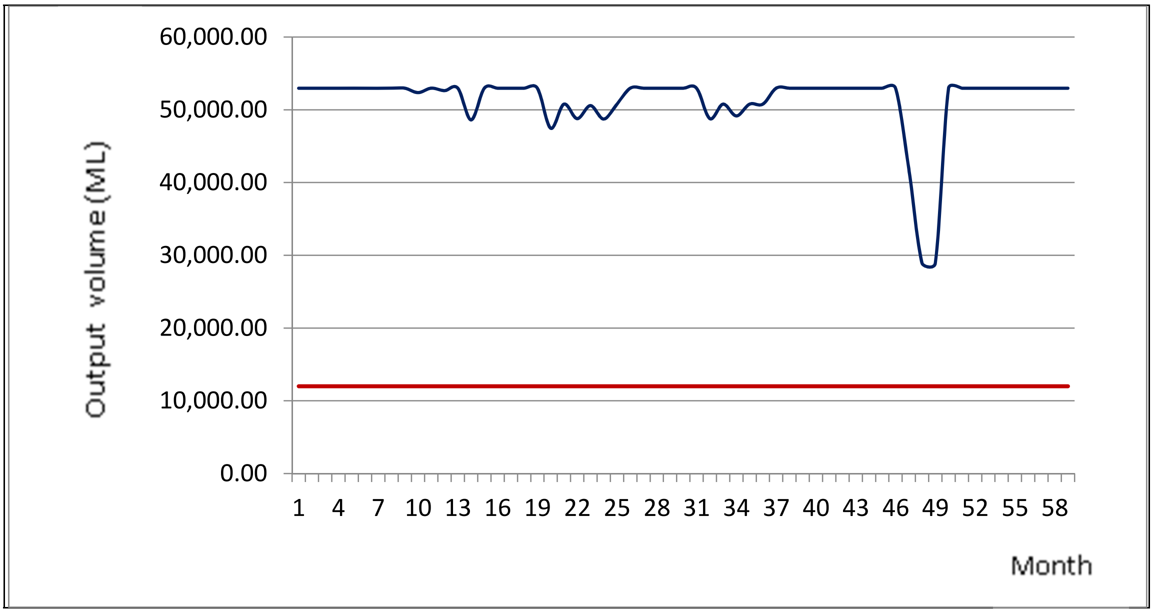

Figure C 8 - Worst case scenario system behaviour (minimum output for each month) for twelve month low rainfall period with reference to the failure threshold (simulated results for SEQ Water Grid for 100% initial storage)

Table C5: Indicator non-failure ratio (Rnf) values

simulation no.	0% storage						50% storage		
	6 months drought%			12 months drought			12 months drought		
	number of failure months (1)	number of non failure months (2)	Rnf = (2)/((1)+(2))	number of failure months (3)	number of non failure months (4)	Rnf = (4)/((3)+(4))	number of failure months (5)	number of non failure months (6)	Rnf = (6)/((5)+(6))
1	10	49	0.831	15	44	0.746	2	57	0.966
2	12	47	0.797	14	45	0.763	2	57	0.966
3	9	50	0.847	14	45	0.763	2	57	0.966
4	11	48	0.814	15	44	0.746	2	57	0.966
5	12	47	0.797	14	45	0.763	2	57	0.966
6	10	49	0.831	15	44	0.746	2	57	0.966
7	8	51	0.864	15	44	0.746	2	57	0.966
8	10	49	0.831	15	44	0.746	2	57	0.966
9	12	47	0.797	15	44	0.746	2	57	0.966
10	8	51	0.864	15	44	0.746	2	57	0.966
11	10	49	0.831	14	45	0.763	2	57	0.966
12	13	46	0.780	14	45	0.763	2	57	0.966
13	13	46	0.780	15	44	0.746	2	57	0.966
14	11	48	0.814	15	44	0.746	2	57	0.966
15	11	48	0.814	14	45	0.763	2	57	0.966
16	12	47	0.797	15	44	0.746	2	57	0.966
17	9	50	0.847	14	45	0.763	2	57	0.966
18	10	49	0.831	15	44	0.746	2	57	0.966
19	11	48	0.814	15	44	0.746	2	57	0.966

Table C5: Continued

simulation no.	0% storage						50% storage		
	6 months drought%			12 months drought			12 months drought		
	number of failure months (1)	number of non failure months (2)	Rnf = (2)/((1)+(2))	number of failure months (3)	number of non failure months (4)	Rnf = (4)/((3)+(4))	number of failure months (5)	number of non failure months (6)	Rnf = (6)/((5)+(6))
20	11	48	0.814	14	45	0.763	2	57	0.966
21	12	47	0.797	15	44	0.746	2	57	0.966
22	10	49	0.831	15	44	0.746	2	57	0.966
23	10	49	0.831	14	45	0.763	2	57	0.966
24	12	47	0.797	14	45	0.763	2	57	0.966
25	11	48	0.814	15	44	0.746	2	57	0.966
26	12	47	0.797	15	44	0.746	2	57	0.966
27	11	48	0.814	14	45	0.763	2	57	0.966
28	12	47	0.797	14	45	0.763	2	57	0.966
29	12	47	0.797	14	45	0.763	2	57	0.966
30	11	48	0.814	14	45	0.763	2	57	0.966
31	12	47	0.797	14	45	0.763	2	57	0.966
32	8	51	0.864	14	45	0.763	2	57	0.966
33	11	48	0.814	15	44	0.746	2	57	0.966
34	8	51	0.864	16	43	0.729	2	57	0.966
35	10	49	0.831	14	45	0.763	2	57	0.966
36	11	48	0.814	14	45	0.763	2	57	0.966
37	12	47	0.797	15	44	0.746	2	57	0.966
38	11	48	0.814	15	44	0.746	2	57	0.966

Table C5: Continued

simulation no.	0% storage						50% storage		
	6 months drought%			12 months drought			12 months drought		
	number of failure months (1)	number of non failure months (2)	Rnf = (2)/((1)+(2))	number of failure months (3)	number of non failure months (4)	Rnf = (4)/((3)+(4))	number of failure months (5)	number of non failure months (6)	Rnf = (6)/((5)+(6))
39	11	48	0.814	16	43	0.729	2	57	0.966
40	11	48	0.814	14	45	0.763	2	57	0.966
41	10	49	0.831	15	44	0.746	2	57	0.966
42	9	50	0.847	15	44	0.746	2	57	0.966
43	12	47	0.797	14	45	0.763	2	57	0.966
44	12	47	0.797	15	44	0.746	2	57	0.966
45	10	49	0.831	15	44	0.746	2	57	0.966
46	9	50	0.847	14	45	0.763	2	57	0.966
47	12	47	0.797	15	44	0.746	2	57	0.966
48	9	50	0.847	14	45	0.763	2	57	0.966
49	9	50	0.847	15	44	0.746	2	57	0.966
50	11	48	0.814	15	44	0.746	2	57	0.966

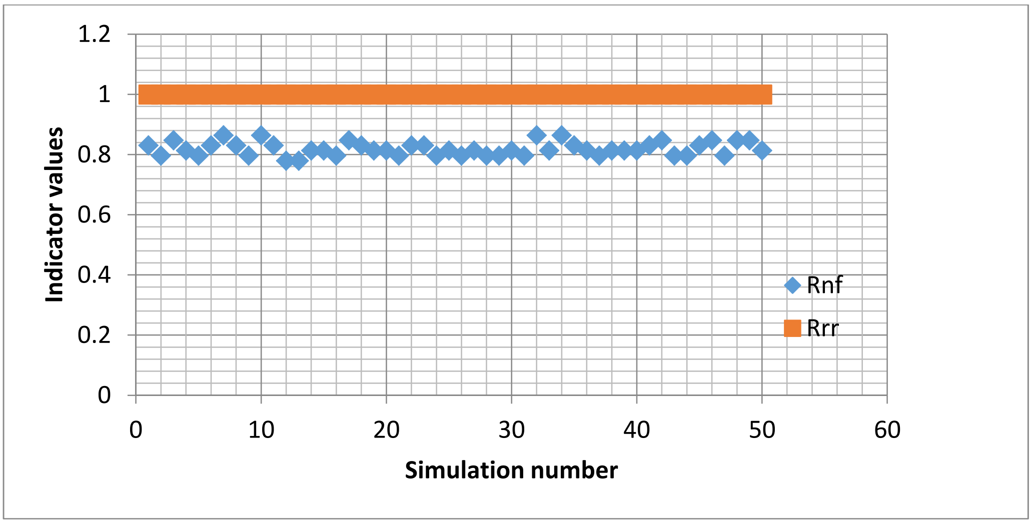

Figure C.9 - Non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for six month low rainfall period (SEQ Water Grid -0% initial storage)

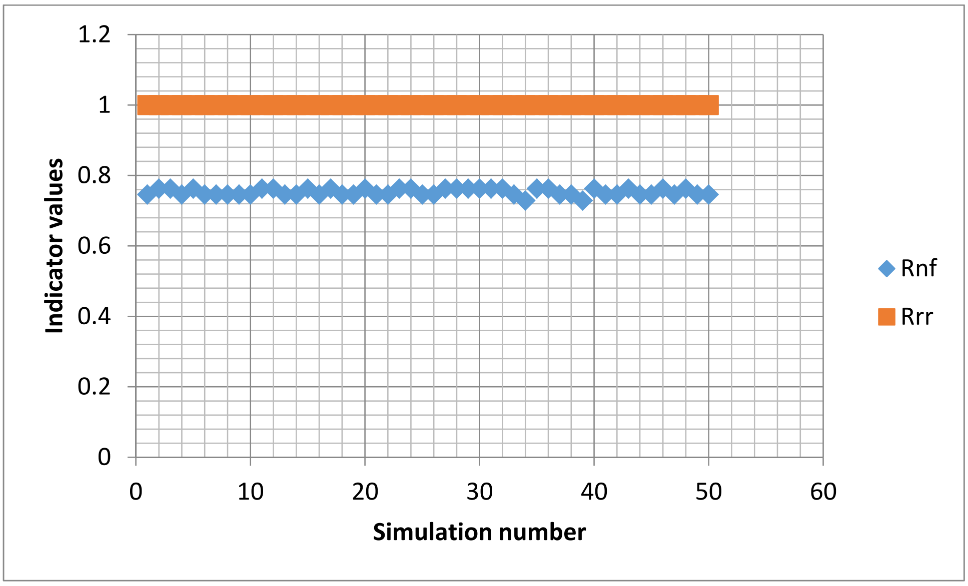

Figure C.10-Non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for twelve month low rainfall period (SEQ Water Grid -0% initial storage)

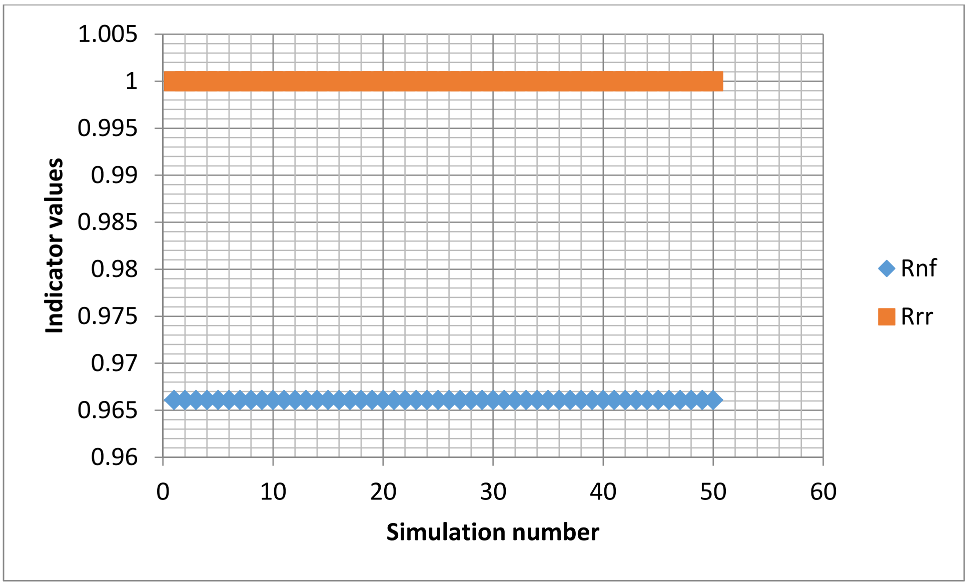

Figure C.11-Non-failure ratio (R_{nf}) and recovery ratio (R_{rr}) for twelve month low rainfall period (SEQ Water Grid -50% initial storage)